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1. REPORT DATE (DD-MM-YYYY) 26-11-2007		2. REPORT TYPE Final		3. DATES COVERED (From - To) 27-03-2007 --- 30-09-2008		
4. TITLE AND SUBTITLE A Megawatt Power Module for Ship Service - Supplement Volume 2				5a. CONTRACT NUMBER N00014-07-C-0361		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Herbst, John D. Gattozzi, Angelo L. Hebner, Robert E.				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The University of Texas at Austin, Center for Electromechanics 10100 Burnet Road, Bldg 133 Austin, TX 78758-4497				8. PERFORMING ORGANIZATION REPORT NUMBER RF280 Volume 2		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 North Randolph Street Arlington, VA 22203-1995				10. SPONSOR/MONITOR'S ACRONYM(S) ONR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for Public Release; Distribution is Unlimited.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT This report is Volume 2 of a three volume Final Report on ONR Contract N00014-07-C-0361. Activities documented in this report were performed as a supplement to ONR Grant N00014-06-01-0886. The two programs address the use of energy storage and high speed power generation to reduce fuel consumption of DDG51 Arleigh Burke class ship service generation system by improving efficiency and permitting safe operation on one gas turbine generator set. In the event of turbine failure, the energy storage unit will provide power for critical loads until a second gas turbine generator set can be brought online. Volume 2 of the Final Report is a User's Manual for the high fidelity MatLab Simulink system simulation model. Volume 1 of the Final Report documents trade studies and preliminary design of the energy storage flywheel and associated motor/generator, the final system topology, high fidelity modeling and simulation activities, and top level platform integration issues. Volume 3 of the Final Report documents projected fuel savings, a preliminary interface control matrix, a ship installation study, and a technology development plan.						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 65	19a. NAME OF RESPONSIBLE PERSON Herbst, John D.	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 512-232-1645	

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Megawatt Power Module for Ship Service Supplement

ONR Contract N00014-07-C-0361

Final Report

Volume 2

MatLab Simulink Simulation User's Manual

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January 2009

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Introduction

The MATLAB Simulink simulation model of the Megawatt Power Module is a deliverable under ONR contract N00014-07-C-036. This document serves as a User's Manual for the simulation, providing descriptions of the various operator inputs and how to modify and execute the simulation. The Simulink model for the MPM was developed and run on a desktop personal computer with Microsoft XP operating system and 2.0 GHz of clock speed. The latest MATLAB/Simulink version and modules used for the MPM simulation are listed in Table 1. The overall model schematic is reported in Figure 1.

Table 1. MATLAB/Simulink version and modules used for the MPM simulation
MATLAB Version 7.6.0.324 (R2008a)
Operating System: Microsoft Windows XP Version 5.1 (Build 2600: Service Pack 2)
Java VM Version: Java 1.6.0 w/ Sun Microsystems Inc. Java HotSpot™ Client VM mixed mode

MATLAB	Version 7.6	(R2008a)
Simulink	Version 7.1	(R2008a)
Control System Toolbox	Version 8.1	(R2008a)
Curve Fitting Toolbox	Version 1.2.1	(R2008a)
Real-Time Workshop	Version 7.1	(R2008a)
Signal Processing Blockset	Version 6.7	(R2008a)
Signal Processing Toolbox	Version 6.9	(R2008a)
SimPowerSystems	Version 4.6	(R2008a)
Simulink Control Design	Version 2.3	(R2008a)
Symbolic Math Toolbox	Version 3.2.3	(R2008a)

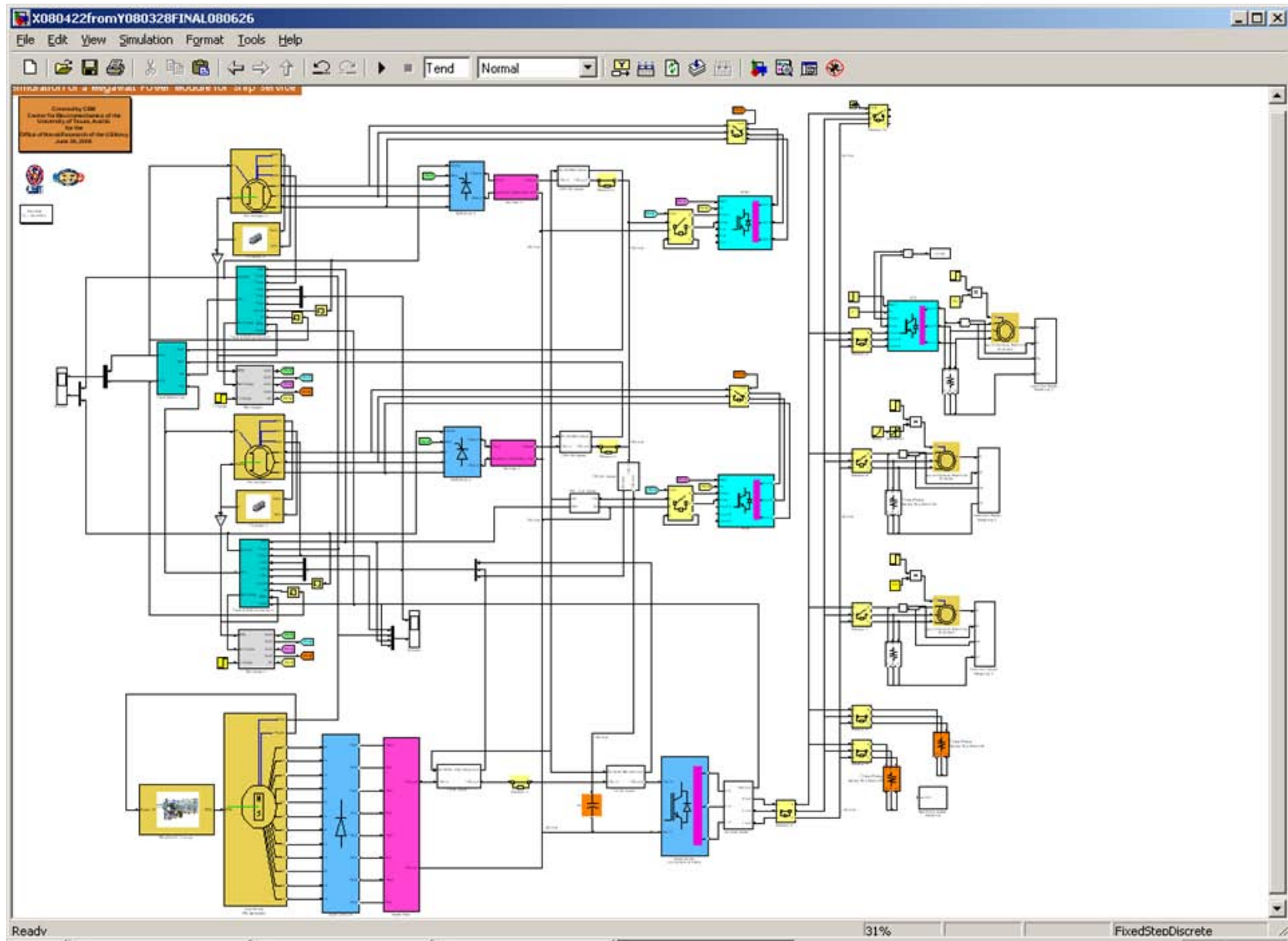


Figure 1. Overall Simulink model diagram

Model Overview

The overall model schematic is reported in Figure 1. This diagram will be examined in detail in subsequent sections. As a general introduction to the simulation model, the following comments apply.

All items germane to a particular function have been combined into one Simulink block with input items pertaining to that block listed in a pop-up dialog box. All details about the construction of the block are available by examining the lower levels within each block.

All blocks with a colored background have a pop-up dialog box associated with them that must be filled out with the appropriate inputs for each run. The only blocks without input dialog box are those with white or gray background, which generally indicate simple measurement or signal routing blocks, and those with bright yellow background, that indicate blocks affected directly by some input variable.

Prior to each run, additional inputs must be entered. These are located in the following two files: `control_law_parameters.m` and `Run001.m`.

`Control_law_parameters.m` contains input items needed by the turbine and should never be changed. It is located in the simulation root directory together with other files needed to support the turbine model.

`Run001.m` contains inputs specific to the current simulation run that can be changed from run to run. It is located in the simulation run directory. The “001” in its name serves as a sequential identifier for the inputs proper to run no. 001. Thus, for example, the next set of values could be stored in file `Run002.m`. The content of file type `RunXXX.m` is explained in the next section of this documentation (Figure 2).

Both files must be run prior to running a simulation. The root directory must also contain all files related to the turbine model (Figure 3). It is recommended that no other files be saved to the root directory except the turbine files and the `control_law_parameters.m` file mentioned above: all simulation specific files including the files type `RunXXX.m` should be saved in separate simulation run directories.

```

Editor - C:\Documents and Settings\alg89654\My Documents\ONR2008\UT_HF_16Jan2008\Run001.m*
File Edit Text Go Cell Tools Debug Desktop Window Help
1 % INPUT ITEMS NEEDED FOR A SIMULATION
2 LVACmin=430; % Minimum AC load Volts line-to-line, V
3 VDCmin=750; % Minimum DC bus voltage, V
4 VDCmax=1100; % Maximum DC bus voltage, V
5 DELTA=250; % Maximum rate of change of DC bus Volts, V/s
6 LIDCmax=4348; % Maximum DC bus load current, A
7 TIDCmax=3623; % Maximum turbine generator DC current, A
8 Ts=0.000002; % Simulation step time, s
9 Tend=10; % Time when simulation ends, s
10 Tcharge=20; % Time when flywheel recharging starts, s
11 T1=20; % Time to activate breaker no. 1, s
12 T2=20; % Time to activate breaker no. 2, s
13 T31=6; % First time to activate breaker no. 3, s
14 T32=8; % Second time to activate breaker no. 3, s
15 T4=20; % Time to activate breaker no. 4, s
16 T5=20; % Time to activate breaker no. 5, s
17 T6=20; % Time to activate breaker no. 6, s
18 T7=20; % Time to activate breaker no. 7, s
19 T8=20; % Time to activate breaker no. 8, s
20 T9=20; % Time to activate breaker no. 9, s

```

Figure 2. The file RunXXX.m in the simulation run directory that must be run before every simulation

Name	Size	Type	Date Modified
slprj		File Folder	6/26/2008 1:06 PM
DFCONSOLE.LIB	9 KB	LIB File	4/10/2003 1:10 AM
DFPORT.LIB	91 KB	LIB File	4/10/2003 1:10 AM
DFORMDD.LIB	172 KB	LIB File	4/10/2003 11:55 AM
DFORMDD.DLL	452 KB	Application Extension	3/26/2007 5:50 PM
Final_11231.tmap.enc	927 KB	ENC File	7/16/2007 3:30 PM
AE1107C_11231.dll	2,080 KB	Application Extension	7/16/2007 4:26 PM
LOAD0_sf.dll	19 KB	Application Extension	7/23/2007 5:06 PM
FPMU_sf.dll	26 KB	Application Extension	7/23/2007 5:17 PM
Subsystem_sf.dll	29 KB	Application Extension	8/2/2007 3:48 PM
ControlLaw_enc_sf.dll	32 KB	Application Extension	8/2/2007 6:11 PM
controlLaw_parameters.m	4 KB	MATLAB M-file	8/6/2007 3:12 PM
UT_HF_16Jan2008.mdl	107 KB	Simulink Model	1/16/2008 4:08 PM
UT_HF_documentation.doc	101 KB	Microsoft Word Doc...	1/16/2008 4:09 PM
MSVCRD.DLL	365 KB	Application Extension	1/23/2008 1:51 PM
DFORMDD.DLL	452 KB	Application Extension	1/23/2008 1:51 PM
Dformt.dll	440 KB	Application Extension	1/23/2008 1:51 PM
UTHF080123.mdl	119 KB	Simulink Model	1/23/2008 2:55 PM
Flywheel.tif	3,592 KB	Microsoft Office Do...	5/16/2008 9:36 AM
Turbine.tif	1,107 KB	Microsoft Office Do...	5/19/2008 9:37 AM
LogoCEM.tif	980 KB	Microsoft Office Do...	6/26/2008 4:49 PM
LogoONR.tif	725 KB	Microsoft Office Do...	6/27/2008 7:46 AM
Run001.asv	2 KB	ASV File	6/27/2008 11:23 AM
Run001.m	2 KB	MATLAB M-file	6/27/2008 11:25 AM

Figure 3. The composition of the simulation root directory - this directory should never be changed

It is also recommended that prior to running a simulation the MATLAB Workspace be cleared. In fact, it is preferable to re-start MATLAB from scratch prior to each simulation to avoid potential carry-over of old data into the new simulation (this problem has been encountered with the turbine model).

Some simplification of the circuit schematic has been achieved by using a small quantity of GoTo/From blocks for some signals. While these blocks simplify visually the circuit

connections, they also make the circuit less immediately intelligible, if used extensively. Thus their use has been limited to few obvious instances.

All variables resulting from the simulation are output to the MATLAB workspace with variable names that attempt to be mnemonic for ease of identification. They are grouped according to the system element to which they refer following the convention below:

- variables related to a flywheel are preceded by the letter F and end with the number 1 or 2, depending on the particular flywheel to which they refer (e.g.: FRPM1 = RPM of flywheel no. 1)
- variables related to the turbine are preceded by the letter T
- variables related to the system electrical load are preceded by the letter L

Also, in general, the presence of the letter V (or I) in the second place indicates that the variable is a voltage (or current). Finally, if the letters are lower case, the real time dependence of the quantity has been captured; if they are capitalized some average or RMS value has been recorded.

The basic configuration parameters used in the preliminary runs is shown in Figure 4. Although other configurations are possible, it was found that the set of parameters shown worked best.

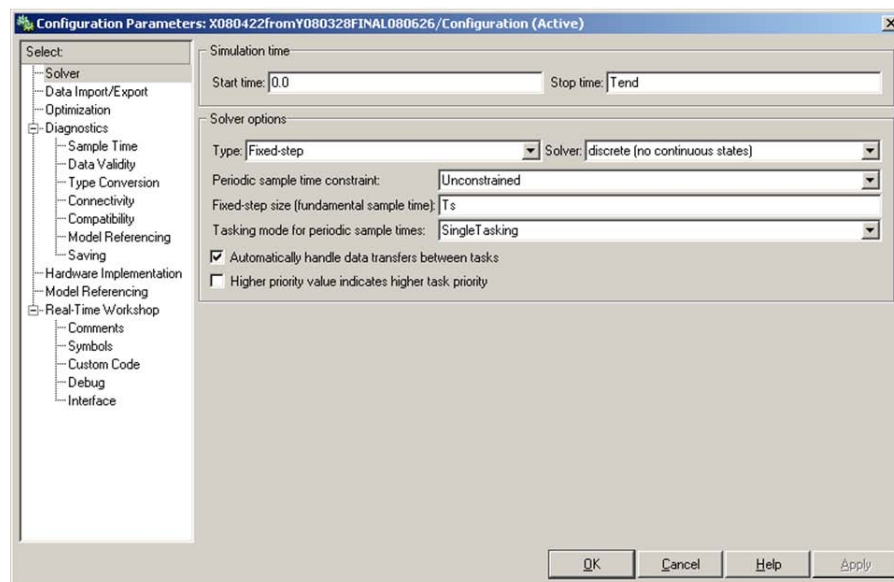


Figure 4. Set of basic configuration parameters used for the simulation

Program inputs and the file RunXXX.m

General Inputs

The items to be entered are listed below together with their program variable name and physical units. As an example, the values used in the preliminary runs are also shown in parenthesis. The file RunXXX.m with the desired inputs must be run prior to starting the simulation.

<i>LVC_{min}, V</i>	Minimum allowable ac line-to-line load voltage (430)
<i>VDC_{min}, V</i>	Minimum allowable dc bus voltage (750)
<i>VDC_{max}, V</i>	Maximum allowable dc bus voltage (1,100)
$\Delta, V/s$	Maximum allowable rate of change of dc bus voltage (250)
<i>LIDC_{max}, A</i>	Maximum allowable dc bus load current (4,348)
<i>TIDC_{max}, A</i>	Maximum allowable dc bus current from turbine generator (3,623)
<i>T_s, s</i>	Simulation step time (2×10^{-6})
<i>T_{end}, s</i>	Time when simulation ends (various, up to 20)
<i>T_{charge}, s</i>	Time when it is desired to start re-charging the flywheels (various, as appropriate)
<i>T1-T9, s</i>	Activation time of breaker no. 1-9 (various, as appropriate). Breakers can change state more than once in a simulation: this has been done, for example, for breaker no. 3, for which two activation times are specified: T31 and T32. If this is desired for other breakers as well, the file RunXXX.m and the breakers' pop-up input box must be changed accordingly.

Inputs Specific to Program Elements

These inputs must be entered via the pop-up dialog boxes associated with the individual model elements. They are listed in the following sections where each element is documented in detail. It is imperative that all inputs be provided before each run and that care be taken that no intrinsic conflict exists among the various inputs for a successful simulation.

Rolls-Royce AE1107 turbine model

The Rolls-Royce AE1107 model used in this simulation tool is a high fidelity model for the turbine whose details are contained in the files provided by Rolls-Royce and located in the simulation root directory (Figure 3). As mentioned above, among these files is the file control_law_parameters.m that must be run in order to properly initialize the turbine model.

Figure 5 shows the turbine block in the simulation circuit and Figure 6 shows the input dialog box that can be obtained by double-clicking on the turbine block.

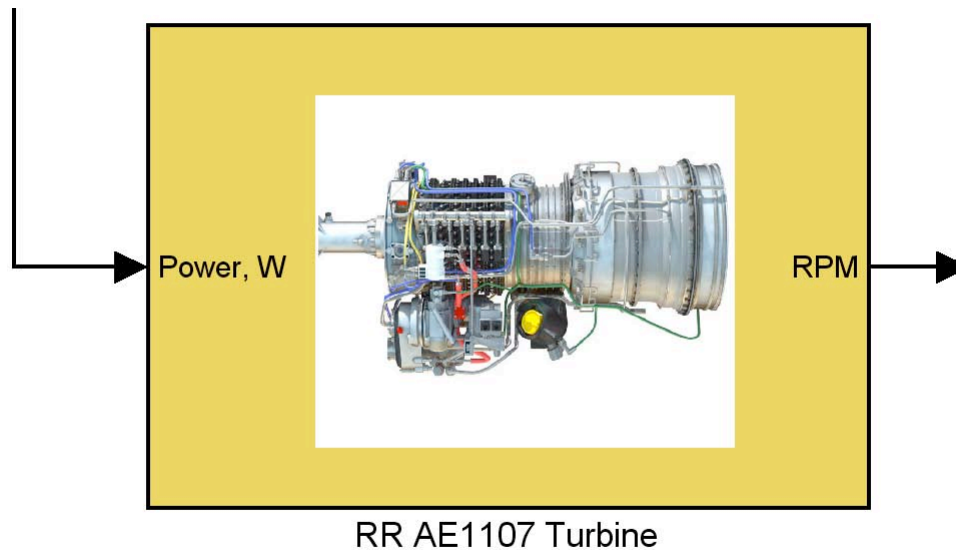


Figure 5. Block representing the high fidelity turbine model

Figure 6. Dialog box for input items of high fidelity turbine model

To view the internal structure of the turbine model, right-click on the block and select “Look under Mask”: the first tier of the structure appears as shown in Figure 7, where it is evident how the input items are fed to the core of the turbine model (dark yellow block).

Double-clicking on this block will provide the information shown in Figure 8 but further clicking on the blocks appearing therein will not produce any additional information: the high fidelity model of turbine AE1107 is a proprietary item of Rolls-Royce and, thus, it is protected.

More information on the turbine model can be obtained reading the Word file UT_HF_documentation.doc to be found in the simulation root directory (Figure 3).

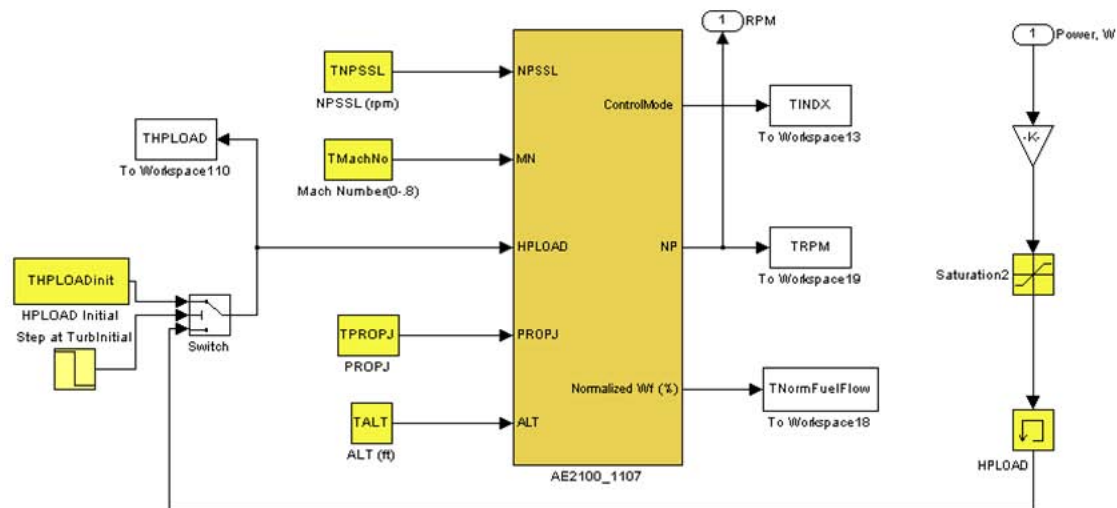


Figure 7. First tier of high fidelity turbine model showing input data fed to core block

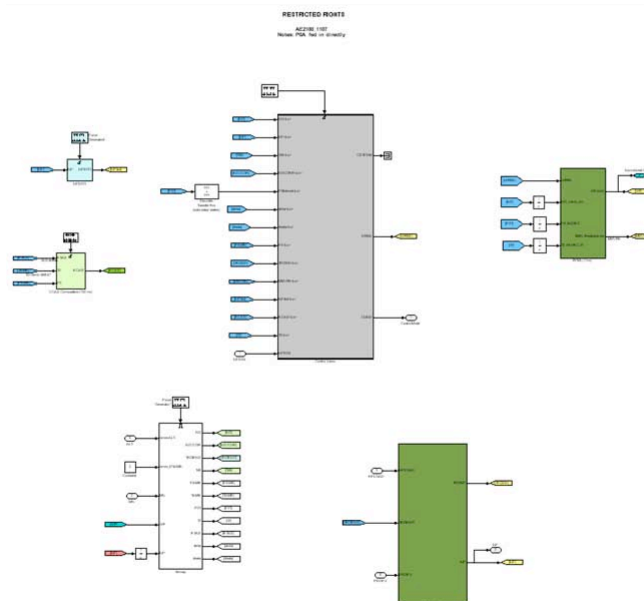


Figure 8. Second tier of high fidelity turbine model - lower level tiers give no additional information as the turbine model is proprietary to Rolls-Royce

Input from and output to other blocks (Figure 5)

<i>Power</i>	Load power in W for the turbine (obtained from the power of the turbine generator). For a number of seconds the turbine runs with a fictitious load until its initialization cycle is complete, at which point it switches to the actual load demanded in the circuit (see dialog box inputs below).
<i>RPM</i>	Turbine shaft RPM used to drive turbine generator

Input items in the dialog box (Figure 6)

(in parentheses are given the values used in preliminary runs)

<i>TNPSSL, RPM</i>	Steady state turbine set speed. For the AE1107 a value between 12,000 and 16,000 RPM is recommended (14,500).
<i>TPROPJ, kg*m²</i>	Inertia of turbine rotating members (2.1739).
<i>TALT, ft</i>	Height above sea level of turbine (0).
<i>TMachNo</i>	Speed in Mach numbers at which the turbine is moving (0).
<i>TurbInitial, s</i>	Time needed for the turbine to initialize properly. Typical values are in the range of $5 \leq t \leq 7$. (5).
<i>THPLOADinit, HP</i>	Fictitious load applied to the turbine during the initialization period. For the AE1107 turbine the suggested value is 3,000 HP (3,000).
<i>THPmax, HP</i>	Turbines maximum permissible load (6,400)
<i>THPmin, HP</i>	Turbine minimum load (1,000). If the actual load falls below this value, the turbine load is kept fictitiously at this floor to avoid instabilities.

Figure 9 shows the variation of the turbine RPM during the turbine initialization period: the turbine load was kept constant in this case so that the speed variation obtained is the result of the turbine initialization only. It can be seen that a minimum of 5 s must be allowed for proper turbine initialization.

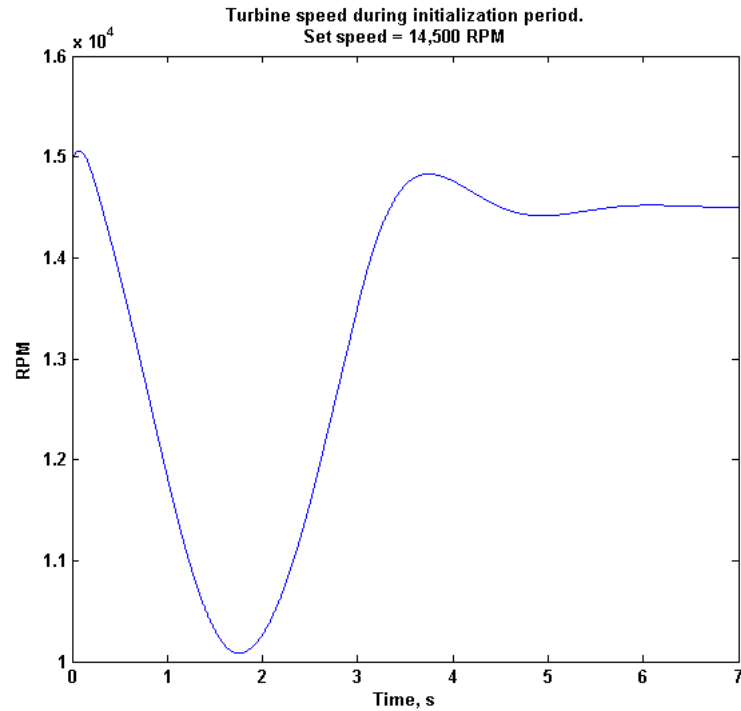


Figure 9. Turbine RPM during initialization with constant load equal to THPLOADinit

Turbine Generator Model

The turbine generator is modeled as a 3-phase permanent magnet synchronous generator with four independent identical stator windings, phase shifted with respect to each other by an electrical phase angle. All stator windings are Y-connected to an internal neutral point. The flux distribution is assumed sinusoidal and the machine is modeled in the dq rotor reference frame. A generator of this type is made by Direct Drive Systems.

Figure 10 shows the icon of the turbine generator in the simulation circuit and Figure 11 shows the input dialog box that can be obtained by double-clicking on the icon. To view the internal structure of the turbine generator model, right-click on the icon and select “Look under Mask”: the first tier of the structure appears as shown in Figure 12. It is evident that the generator is modeled as four independent PM generators (dark yellow blocks) which are essentially native Simulink models modified to accept a phase input. The phase inputs are shown in the bright yellow blocks. Each elementary generator has to be artificially loaded with a resistive 3-phase load in order to maintain computational stability. The load used consists of

1,000 Ω to neutral per phase per generator. Although this additional load is the source of a systematic error in the calculations for most practical simulations, its impact on the results will be negligible. Figure 12 shows the first tier of turbine generator block showing the four independent PM generators (dark yellow blocks) with phase inputs (bright yellow blocks). Several measurement blocks are in white: their structure is accessible and rather obvious so as not to need special description. Also visible are the resistive loads at the generator terminals needed to maintain computational stability. These loads would not be needed in the actual hardware.

Double-clicking on the individual PM generators will bring up a pre-filled dialog box that need not be changed. Right-clicking on the elementary PM generator blocks will provide the information shown in Figure 13 that shows the modification made to allow the phase input. Figure 13 shows the second tier of turbine generator model with the internal structure of each component PM generator. The circuit native to Simulink had to be altered (area in light blue) to allow the input of a phase angle. Lower level tiers are accessible for the blocks in white, although they are not affected directly by user's inputs and are not discussed herein.

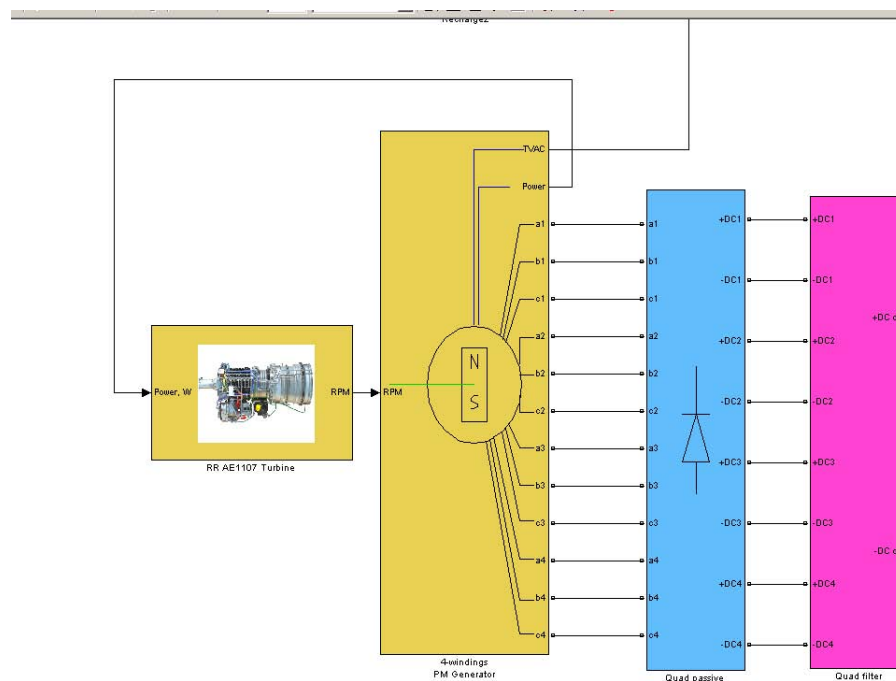


Figure 10. Block representing the turbine generator shown between the turbine and the rectifier blocks

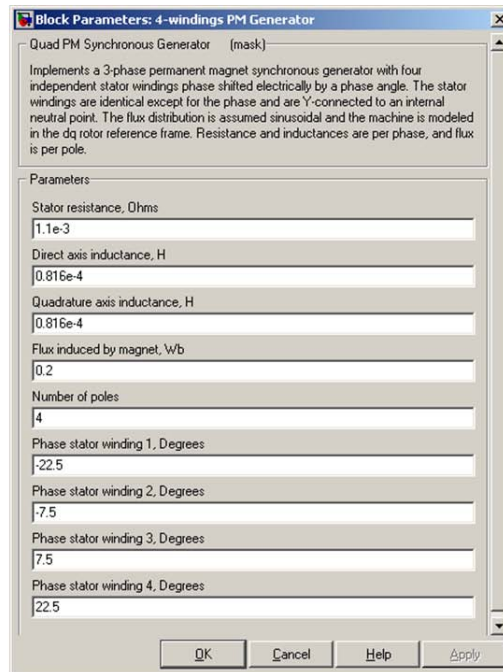


Figure 11. Dialog box for input items of turbine generator

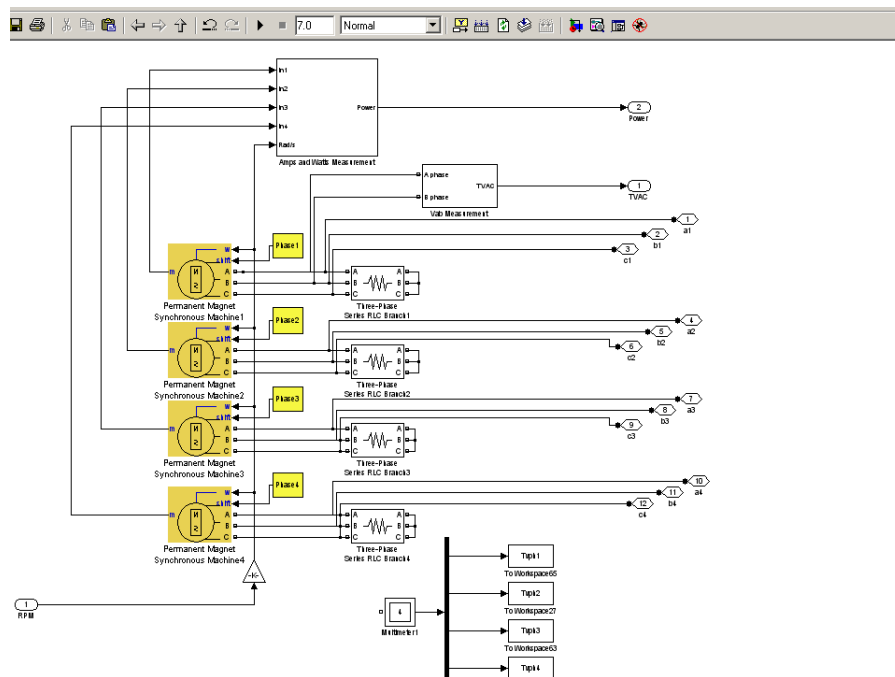


Figure 12. First tier of turbine generator block showing the four independent PM generators (dark yellow blocks) with phase inputs (bright yellow blocks)

Input items in the dialog box (Figure 11)

(in parentheses are given the values used in preliminary runs)

R_s, Ω	<i>Stator resistance per phase of each individual component winding (0.0011).</i>
L_d, H	<i>Direct axis inductance per phase of each individual component winding ($0.816 \cdot 10^{-4}$).</i>
L_q, H	<i>Quadrature axis inductance per phase of each individual component winding ($0.816 \cdot 10^{-4}$).</i>
Flux, Wb	<i>Flux induced by magnet per pole per phase of each individual component winding (0.2).</i>
p	<i>Number of poles of each individual component generator (4).</i>
$\text{Phase 1-4, Degrees}$	<i>Electrical phase angle of each component winding (-22.5, -7.5, 7.5, 22.5).</i>

An example of turbine generator output with the input values listed above can be seen in Figure 14.

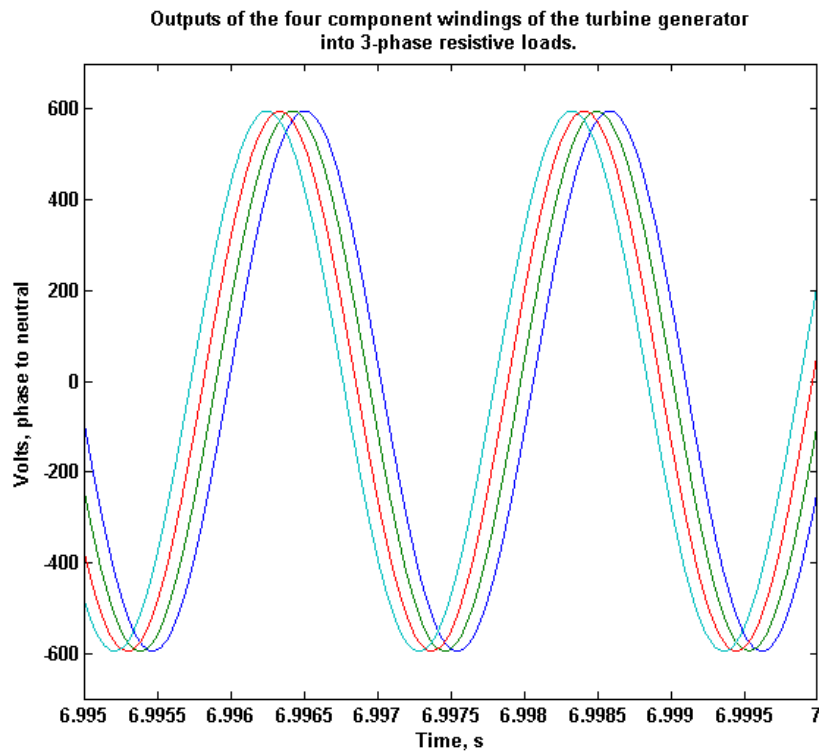


Figure 14. Typical output of turbine generator into a resistive load

Quad Passive Rectifier

The output of each individual winding of the turbine generator is rectified individually by a passive 3-phase diode rectifier. The quad passive rectifier block is shown in Figure 15 and its dialog box in Figure 16. In general, once determined, the values entered in this input dialog box rarely need to be changed. Figure 14 shows the internal structure of the rectifier.

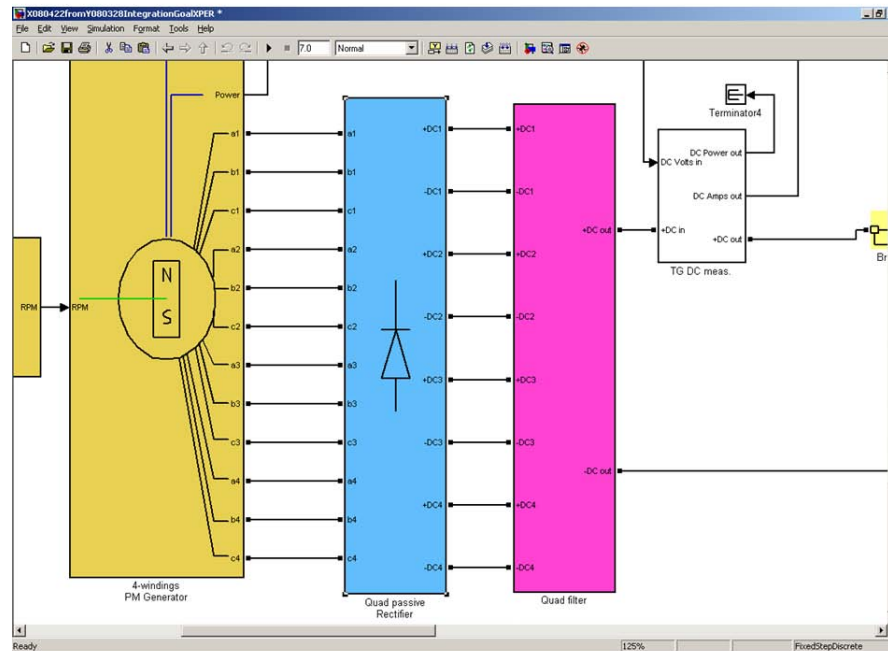


Figure 15. Quad passive rectifier and quad filter blocks following downstream the turbine generator block

Figure 16. Dialog box for input items of quad passive rectifier - these items are rarely changed

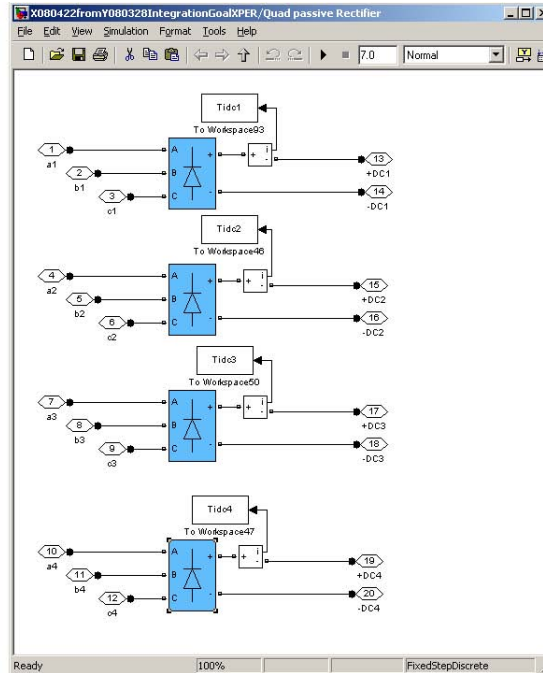


Figure 17. First tier of quad passive rectifier - the individual diode rectifiers (blue) are native Simulink blocks, thus no further tiers are accessible, white blocks are for measuring currents

Input from and output to other blocks (Figure 15):

- | | |
|-----------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| a_k, b_k, c_k | 3-phase AC outputs from the four individual turbine generator windings ($k = 1, 2, 3, 4$) connected as inputs to the rectifier block. |
| $+DCk, -DCk$ | DC outputs from each individual rectifier ($k = 1, 2, 3, 4$). |

Input items in the dialog box (Figure 16)

(in parentheses are the values used in preliminary runs)

- | | |
|--------------------|---------------------------------------------------------------------------------------|
| $R_s Q, \Omega$ | Snubber resistance: each diode has an individual RC snubber (100). |
| $C_s Q, F$ | Snubber capacitance: each diode has an individual RC snubber ($0.1 \cdot 10^{-6}$). |
| $R_{on} Q, \Omega$ | On resistance for each diode (0.001). |
| $L_{on} Q, H$ | On inductance for each diode: typically equal to zero (0). |
| $V_{on} Q, V$ | On forward voltage for each diode (0.8). |

An example of voltages at the turbine generator outputs (inputs to rectifier) and at the rectifier outputs into a resistive load can be seen in Figure 18.

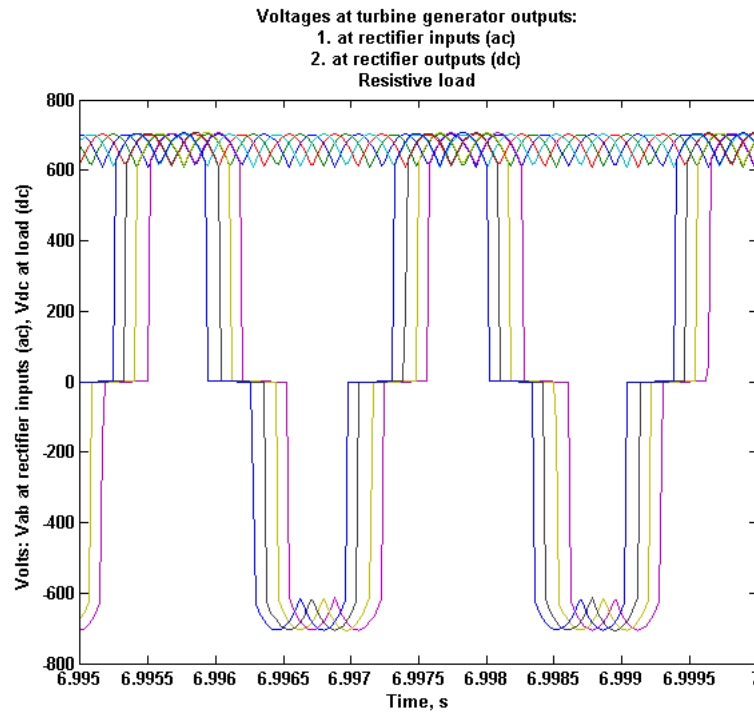


Figure 18. Typical voltages input to the turbine generator rectifier and from it output into a resistive load

Quad Filter

The output of each rectifier is individually connected to the dc bus via a filter. The quad filter block is shown in Figure 15 immediately following the quad rectifier and its dialog box is shown in Figure 19. The first tier diagram is shown in Figure 20 while the next and last level showing the composition of each T-filter is shown in Figure 21.

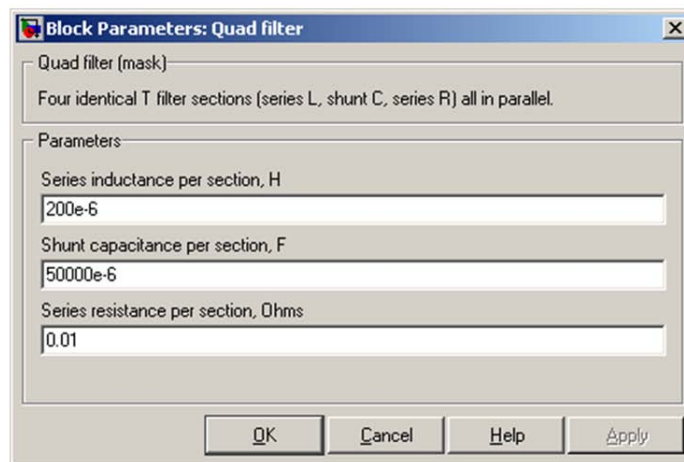


Figure 19. Input dialog box of quad filter

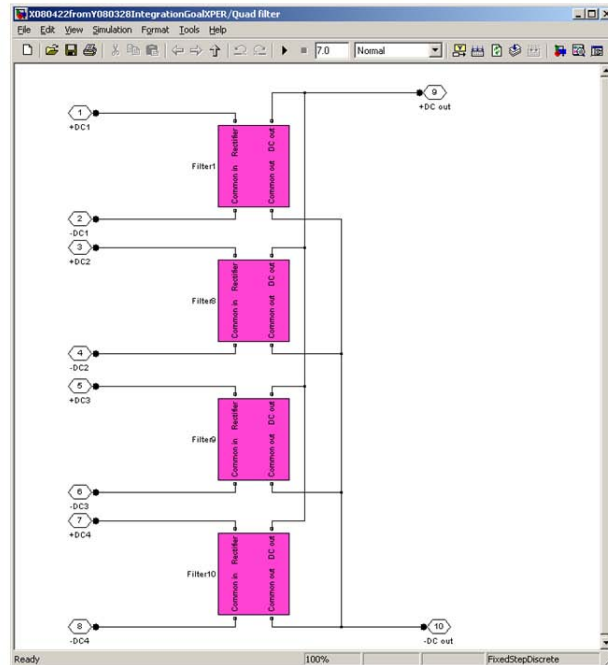


Figure 20. Structure of the quad filter

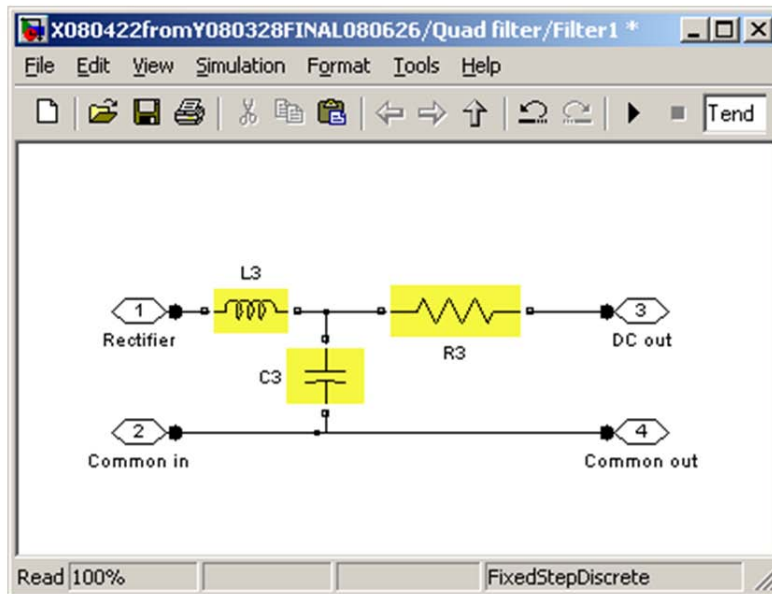


Figure 21. Diagram of individual T-type filter within the quad filter

Input from and output to other blocks (Figure 15):

$+DCk$, $-DCk$ DC inputs from each individual rectifier section of the quad rectifier ($k = 1, 2, 3, 4$).

+DC out, -DC out DC bus output connection points.

Input items in the dialog box (Figure 19 and Figure 21):

(in parentheses are the values used in preliminary runs)

L3, H Series inductance per section ($200 \cdot 10^{-6}$).

C3, F Shunt capacitance per section ($50,000 \cdot 10^{-6}$).

R3, Ω Series resistance per section (0.01).

DC Bus, Quad DC-AC Converter with Filter, and AC Bus

The output of the quad filter is connected, via a measurement block, to the dc bus capacitor which is followed by a quad dc-ac converter with filter. The output of this converter is the ac bus where the loads are connected (Figure 22).

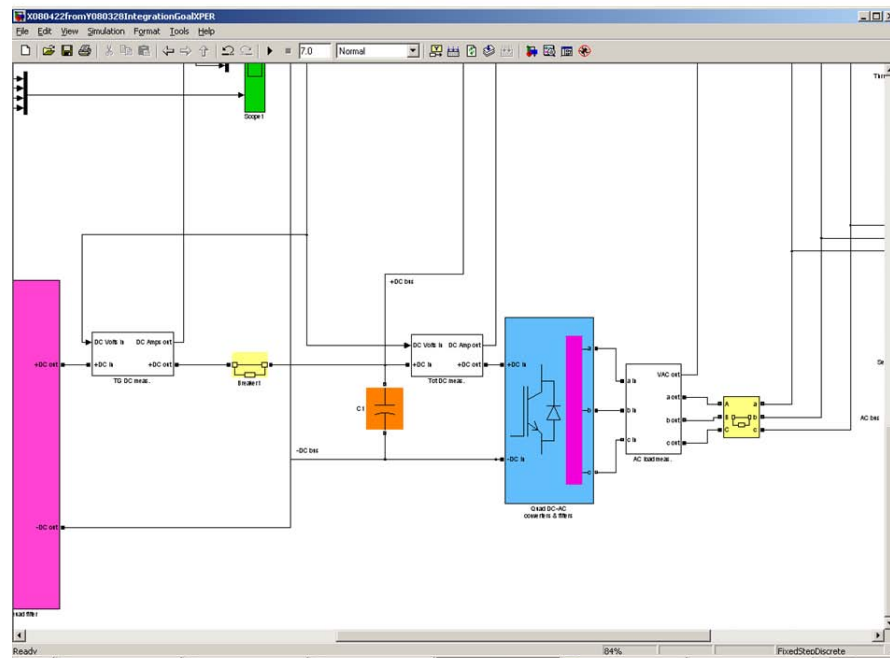


Figure 22. dc bus, quad dc-ac converter with filter, and ac bus - White blocks are used for measurements and bright yellow blocks are ideal breakers whose switching times are settable

The dialog box of the dc-ac quad converter is shown in Figure 23. This converter is a multi-tiered block built up with native Simulink blocks and this documentation will show all levels of interest for the proper operation of the model. The first tier diagram is shown in Figure 24. The four IGBT converter bridges (blue) operate in parallel and have individual output filters (purple)

and a common PWM controller (cyan), The filters are connected together at their output to form the ac bus after a measurement block (white).

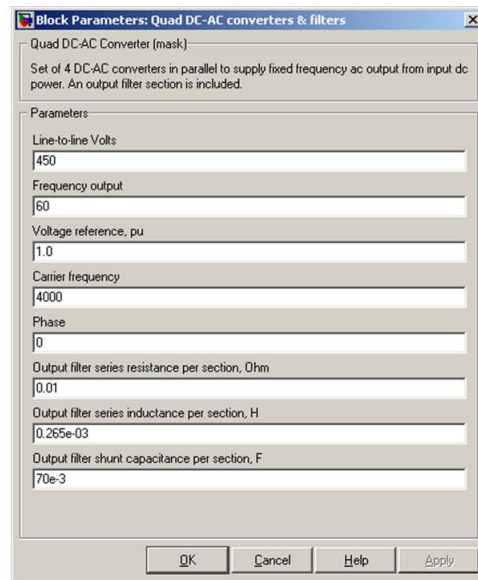


Figure 23. Input dialog box for the quad dc-ac converter with filter

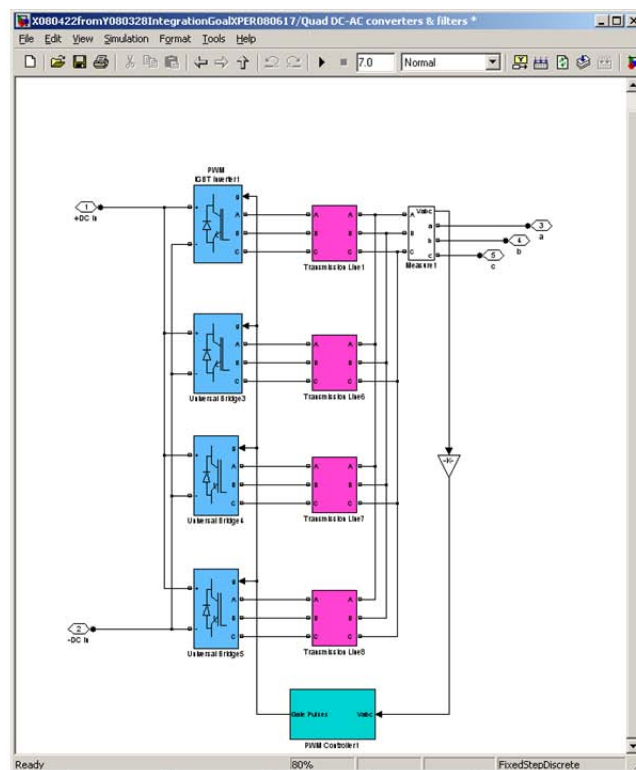


Figure 24. First level of quad dc-ac converter with filter

The dialog box of one of the IGBT bridges is shown in Figure 25 and is the same for all bridges. In general, once determined, the values entered in this input dialog box rarely need to be changed. The IGBT bridge is a native Simulink block. Figure 26 shows the circuit of the four identical output filters.

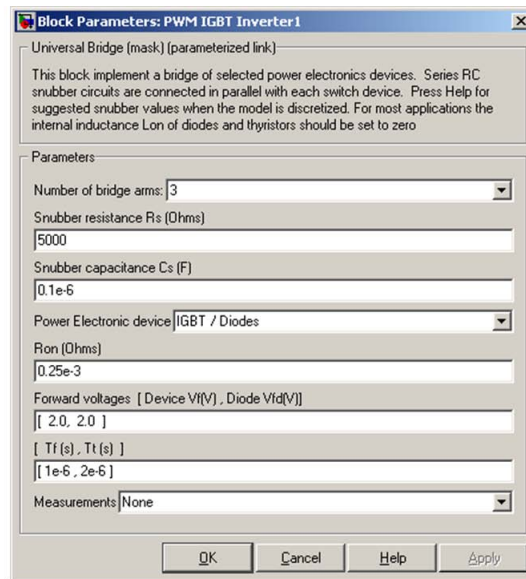


Figure 25. Input dialog box for one of the IGBT bridges - once determined, these rarely need to be changed

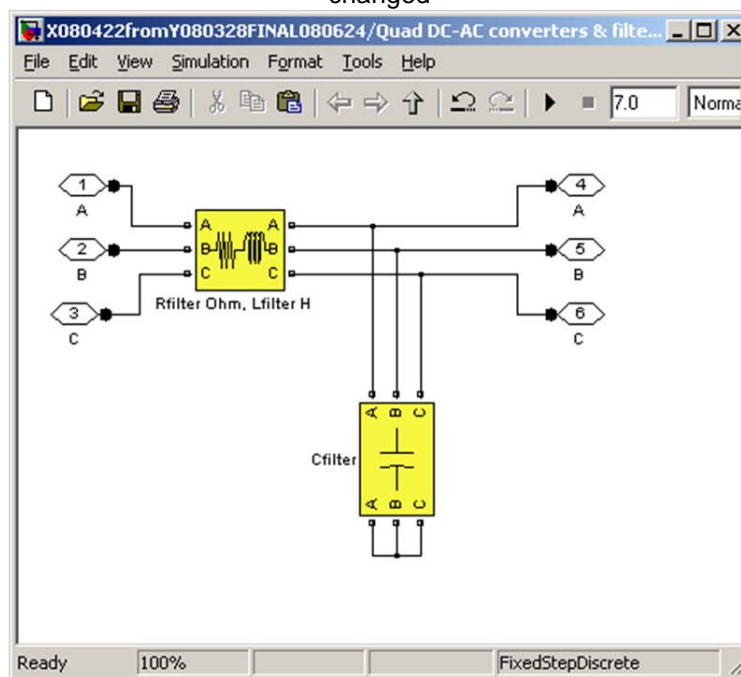


Figure 26. circuit diagram of one of the output filters of the quad dc-ac converter

The four IGBT bridges are driven by the same PWM controller, whose structure is shown in Figure 27. This is a multi-level block and here only those items that are affected directly by the input data under the control of the user will be commented (highlighted, as usual, in bright yellow).

The discrete PWM pulse generator is affected by the input for the frequency of the triangular waveform carrier signal in the dialog box of Figure 23.

The reference voltage, also specified in the same figure, is seen to be an input to the voltage regulator block whose input dialog box is shown in Figure 28 and whose structure is shown in Figure 29. Here the PI controller block is affected by the values entered for the proportional gain and integral gain in the dialog box of Figure 28, while the PLL block is affected by the values for output frequency and phase entered in the dialog box of Figure 23. It is recommended that none of the dialog boxes attached to blocks at levels below the main portal shown in Figure 23 be altered as the values used have been proven to give the best results: normally, the user should enter values only through the dialog box shown in Figure 23. Many of the blocks left with white background have additional structures of their own but are not directly affected by the input items and are not discussed further herein.

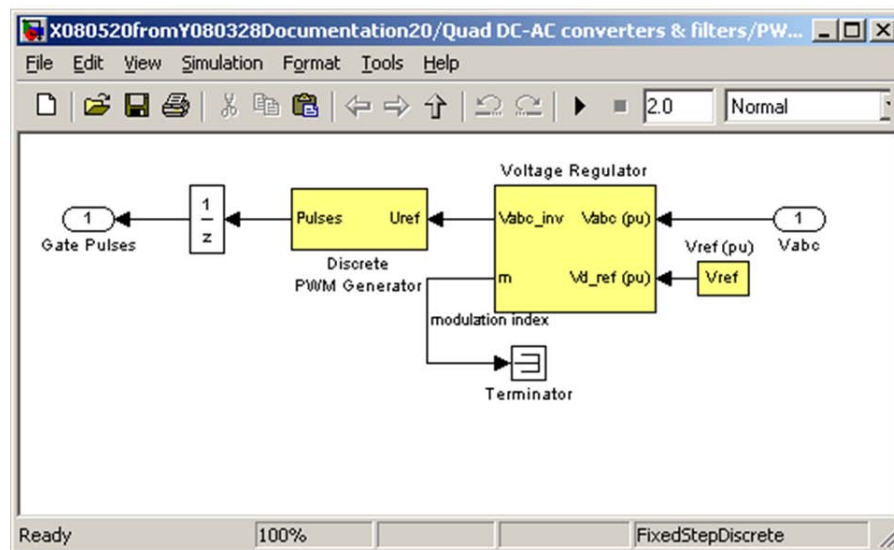


Figure 27. Structure of PWM controller of Figure 24

Although the PWM Generator and the Voltage Regulator blocks (both bright yellow) have input dialog screens of their own, it is not necessary or advisable to change them.

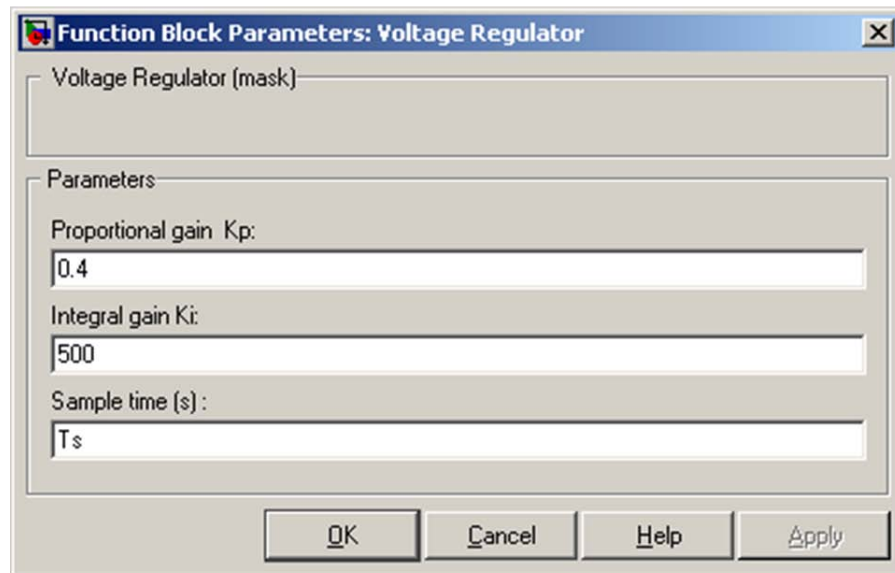


Figure 28. Dialog box for voltage regulator block in Figure 27 - the values shown (affecting the PI block in Figure 29) have been proven to give the best results, thus, normally they should not be changed

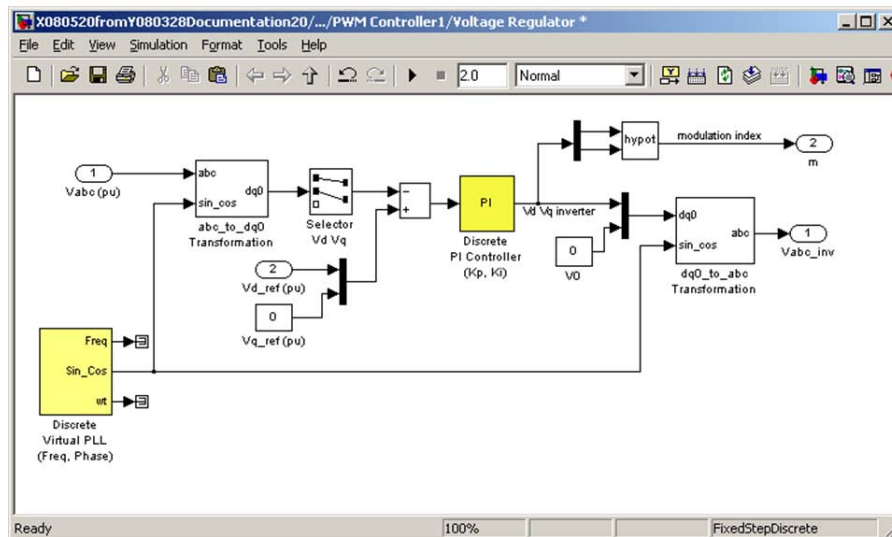


Figure 29. Internal diagram of voltage regulator block shown in Figure 27 - although the PLL and the PI blocks (both bright yellow) have input dialog screens of their own, it is not necessary or advisable to change them

Input from and output to other blocks (Figure 22):

<i>+DC out, -DC out</i>	DC bus inputs from the turbine generator quad filter via a measurement block (white) and an ideal breaker with settable switching times (bright yellow). Contributions to the DC bus come also from the flywheel sections (see further below).
<i>a, b, c</i>	Three phase output to the ac bus by way of a measuring block (white) and an ideal breaker with settable switching time (bright yellow).

Input items in the main portal dialog box (Figure 23, Figure 26, Figure 27):

(in parentheses are the values used in preliminary runs)

<i>VLL, V</i>	Desired output line-to-line voltage on the ac bus (450).
<i>Freq, Hz</i>	Desired frequency of output ac power (60)
<i>Vref, pu</i>	Reference level of voltage regulator, in per unit of the rated output voltage on the ac bus (1.00)
<i>Fc, Hz</i>	Frequency of carrier triangular waveform generating PWM pulses (4000)
<i>Phase, Degrees</i>	Electrical phase angle of output ac bus voltages (0)
<i>Rfilter, Ω</i>	Output filter series resistance per section (0.01)
<i>Lfilter, H</i>	Output filter series inductance per section ($0.265 \cdot 10^{-3}$)
<i>Cfilter, F</i>	Output filter shunt capacitance per section ($70 \cdot 10^{-3}$)

Input items in the IGBT bridges dialog boxes (Figure 24 and 25):

(in parentheses are the values used in preliminary runs)

<i>Snubber resistance, Ω</i>	Each IGBT has an individual RC snubber (5000).
<i>Snubbercapacitance, F</i>	Each IGBT has an individual RC snubber ($0.1 \cdot 10^{-6}$).
<i>On resistance, Ω</i>	For each IGBT ($0.25 \cdot 10^{-3}$).
<i>Onforward voltage, V</i>	For each IGBT (2.0) and free-wheeling diode (2.0).
<i>Fall time and tail time, s</i>	For each IGBT ($1.0 \cdot 10^{-6}$, $2.0 \cdot 10^{-6}$)

An example of the output available on the ac bus is given in Figure 30, Figure 31, Figure 32 that were generated varying a 3-phase resistive load in a step-wise fashion across the bus as follows:

$0 < t < 0.4 \text{ s}$	0 Amps (no-load)
$0.4 < t < 0.7$	1,918 Amps (~1.5MW load)
$0.7 < t < 1.0 \text{ s}$	3,836 Amps (~3.0 MW load)

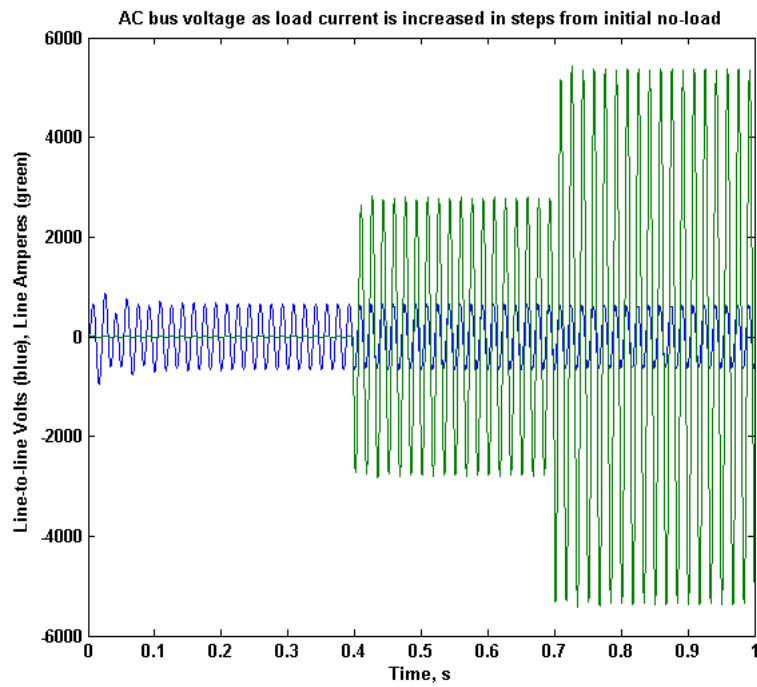


Figure 30. AC bus voltage as load current is stepped up from initial no-load

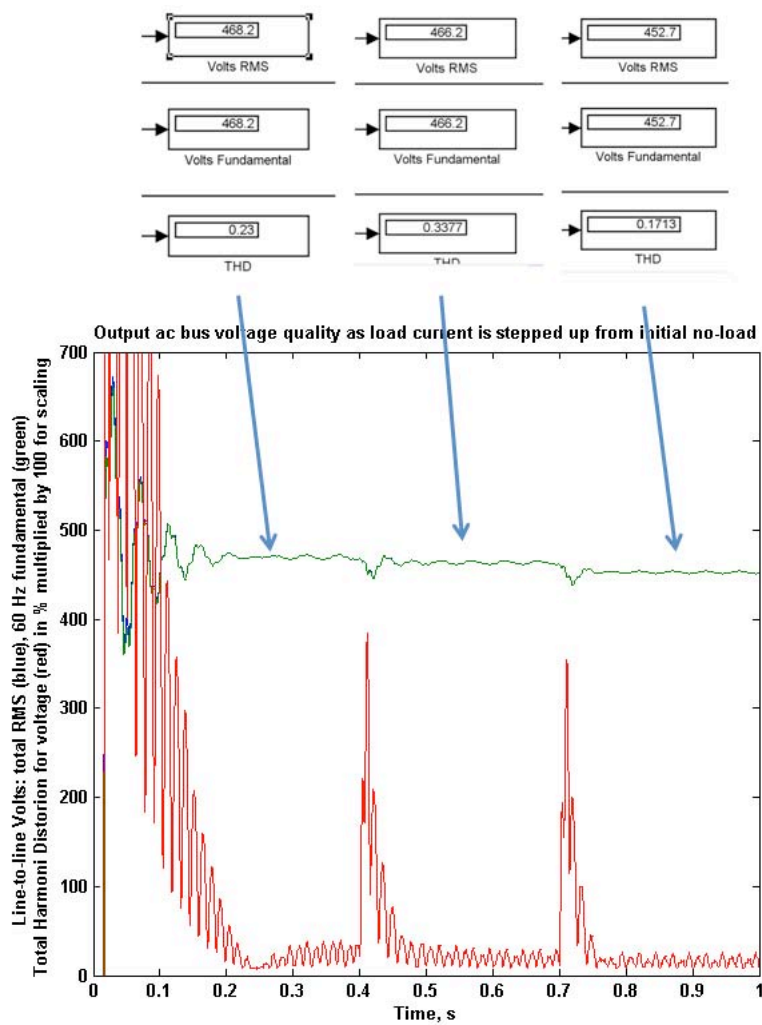


Figure 31. AC bus total voltage RMS (blue) and fundamental voltage only (green) as load current is stepped up from initial no-load. Blue and green traces overlap, indicating minimal harmonic contents. Total harmonic distortion (THD) is shown in red times a factor of 100 for scaling purposes. Thus, ignoring the initial settling transient ($t < 0.2$ s) the THD is always less than 4%. Actual simulation readouts are also shown above.

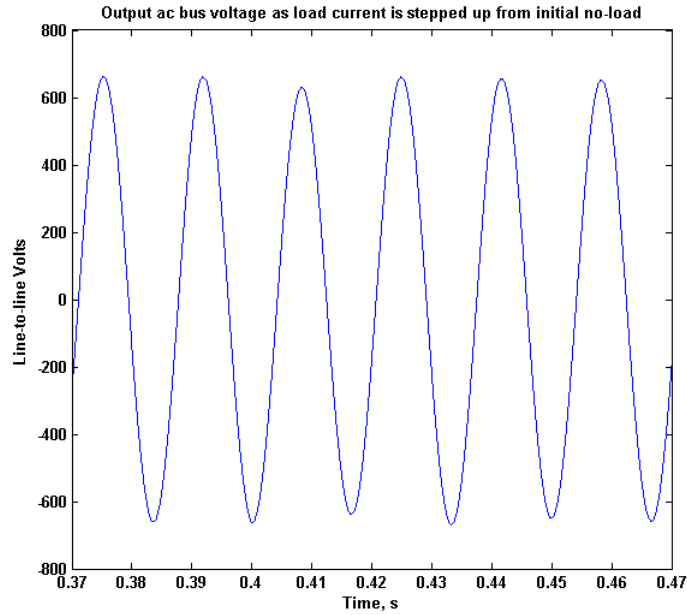


Figure 32. Detail of ac voltage waveform at the current transition point $t = 0.4$ s

Flywheel

The model for the flywheel used in this simulation tool is a direct application of the mechanical equations governing its behavior. Figure 33 shows the flywheel block in the simulation circuit and Figure 34 shows the input dialog box that can be obtained by double-clicking on it. To view the internal structure of the flywheel model, right-click on the block and select “Look under Mask”: its configuration appears, as shown in Figure 35. Further double-clicking on the dark yellow block in Figure 35 opens its second (and last) level as shown in Figure 36.

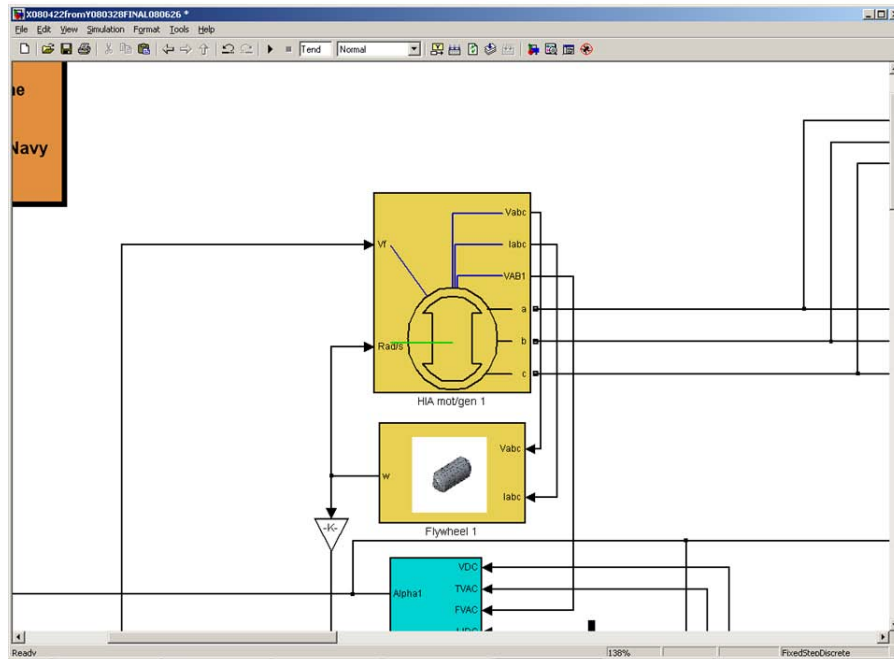
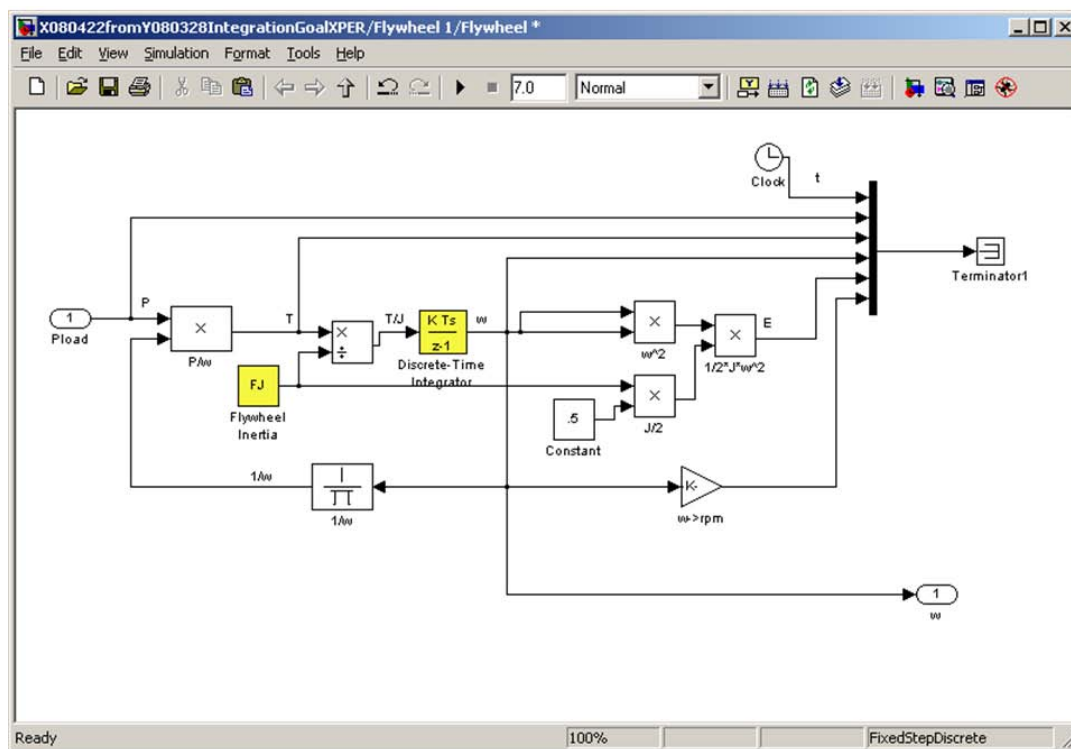
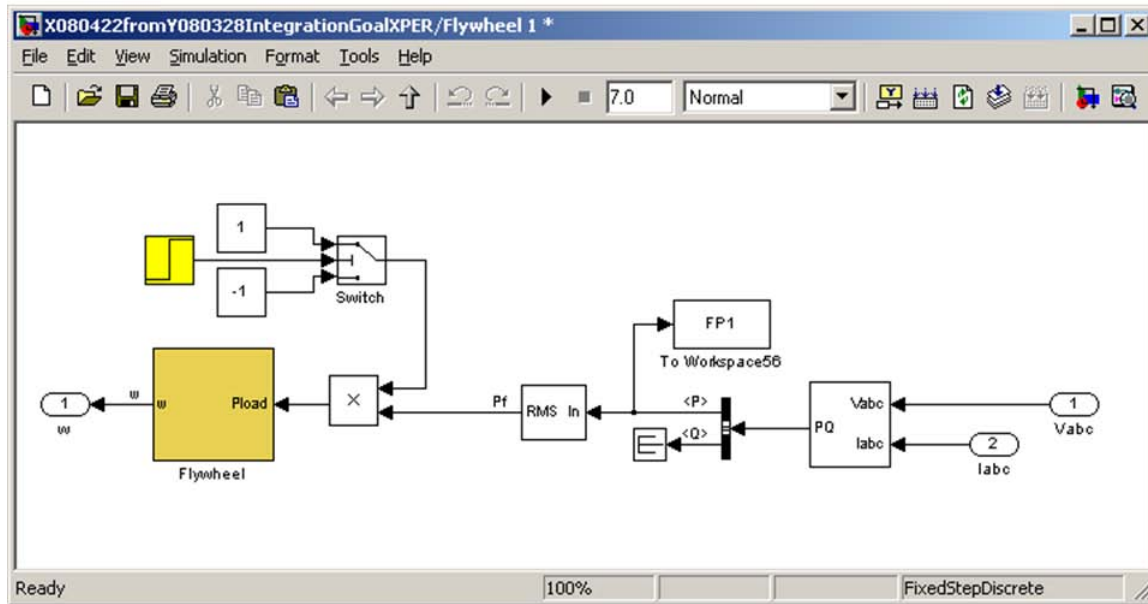


Figure 33. One of the two flywheels in the simulation circuit with its motor/generator

The dialog box is titled 'Function Block Parameters: Flywheel 1'. It contains a description: 'Flywheel (mask) Calculates the mechanical state of a flywheel'. Under the 'Parameters' section, there are two input fields: 'Flywheel Inertia kg*m^2' with the value '398' and 'Flywheel initial speed, rpm' with the value '12000'. At the bottom, there are buttons for 'OK', 'Cancel', 'Help', and 'Apply'.

Figure 34. Dialog box for flywheel data input



Input from and output to other blocks (Figure 33):

V_{abc}, V	3-phase AC voltage inputs from the flywheel motor/generator.
I_{abc}, A	3-phase AC current inputs from the flywheel motor/generator.
$\omega, rad/s$	Flywheel speed, output to motor/generator.

Input items in the dialog box (Figure 34):

(in parentheses are the values used in preliminary runs)

$FJ, kg*m^2$	Flywheel inertia (398).
ω_0, RPM	Flywheel initial speed (12,000).

Flywheel Motor/Generator Model

The flywheel motor/generator is modeled as a 3-phase wound field synchronous generator with a stationary field winding as in the topology known as homopolar inductor alternator (hereinafter indicated by its acronym HIA: see body of final report for details). The machine is modeled in the dq rotor reference frame. A generator of this type is not known to be available in the market at this time, thus, its basic parameters had to be estimated from a preliminary design.

The block for the flywheel motor/generator in the simulation circuit is shown in Figure 33, Figure 37 shows the input dialog box that can be obtained by double-clicking on the icon. To view the internal structure of the flywheel motor/generator model, right-click on its icon and select “Look under Mask”: the first tier of the structure appears as shown in Figure 1.

Block Parameters: HIA mot/gen 1

HIA motor/generator (mask)

Model for a 3-phase homopolar inductor alternator synchronous machine. The machine is modeled in the rotor dq reference frame. Quantities are on a per-phase equivalent Y.

Parameters:

Rated KiloVolAmperes	1250
Rated Volts line-to-line, RMS	634
Rated Frequency, Hz	400
Rated Field Amperes dc	22.6
Stator Resistance, Ohms per phase	1.345e-3
Stator Leakage Inductance, H per phase	2.956e-5
Direct Axis Magnetizing Inductance, H	2.509e-4
Quadrature Axis Magnetizing Inductance, H	1.676e-4
Field Resistance, Ohms	1.227e-3
Field Leakage Direct Axis Inductance, H	5.643e-5
Equiv. Damper Direct Axis Resistance, Ohms	0.340
Equiv. Damper Leakage Direct Axis Inductance, H	3.372e-4
Equiv. Damper Quadrature Axis Resistance, Ohms	0.025
Equiv. Damper Leakage Quadrature Axis Indu	7.18e-5
Number of poles	4
Initial Electrical Angle of Rotor, Degrees	0

OK Cancel Help Apply

Figure 37. Input dialog box for the flywheel motor/generator modeled in the rotor dq frame of reference

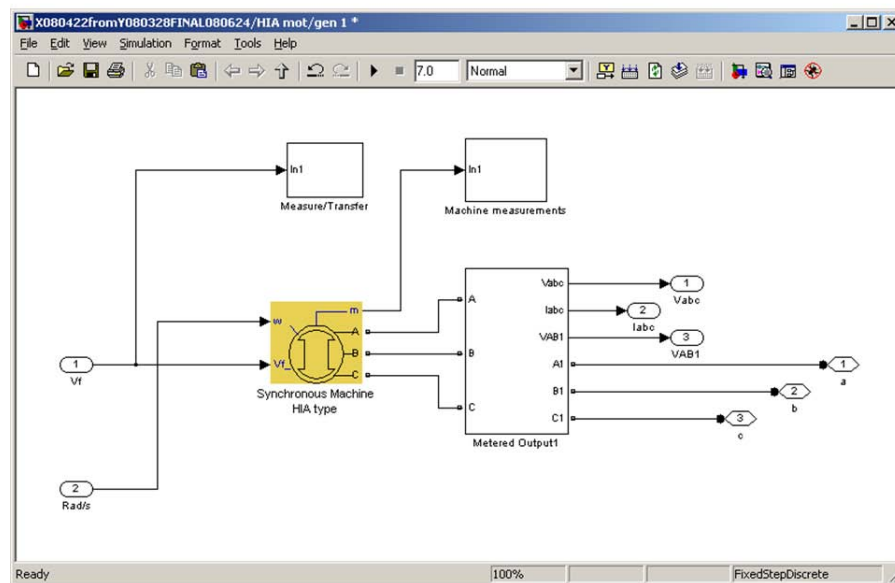


Figure 38. First level structure of flywheel motor/generator. The machine is modeled as a standard Simulink wound field synchronous machine (dark yellow block) with three measurement blocks (white).

The motor/generator is modeled as a standard synchronous wound field machine (dark yellow block) native to Simulink but its inputs, of course, must reflect the characteristics of the homopolar construction. Double-clicking on the synchronous machine block generators will bring up a pre-filled dialog box that needs not be changed (Figure 39).

The white blocks are for measurements and their contents are shown in Figure 1. It can be seen that, as was the case for the turbine generator, the flywheel motor/generator also has to be artificially loaded with a resistive 3-phase load in order to maintain computational stability. However, here the problem is more severe as it was found experimentally that the load needed was 25Ω to neutral per phase: any larger resistor seemed to produce instability problems. This additional fixed load, of course, is fictitious and the source of a systematic error in the calculations. Even so, this error was found to be typically less than 3%, thus negligible in most cases of practical interest.

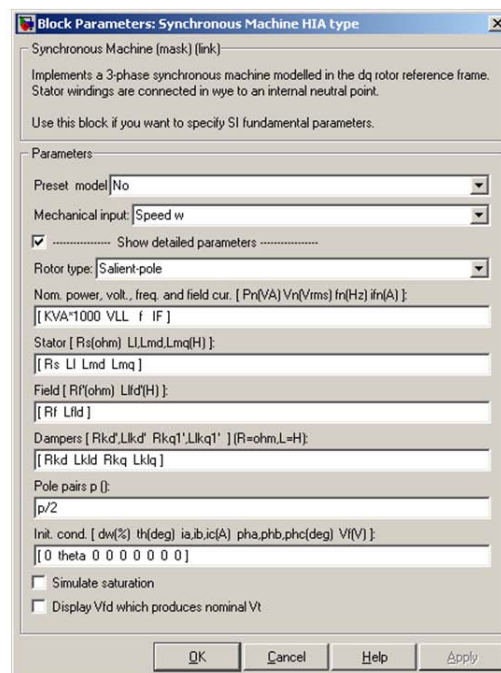


Figure 39. Pre-filled dialog box of synchronous machine shown in Figure 38 - these inputs should never be changed

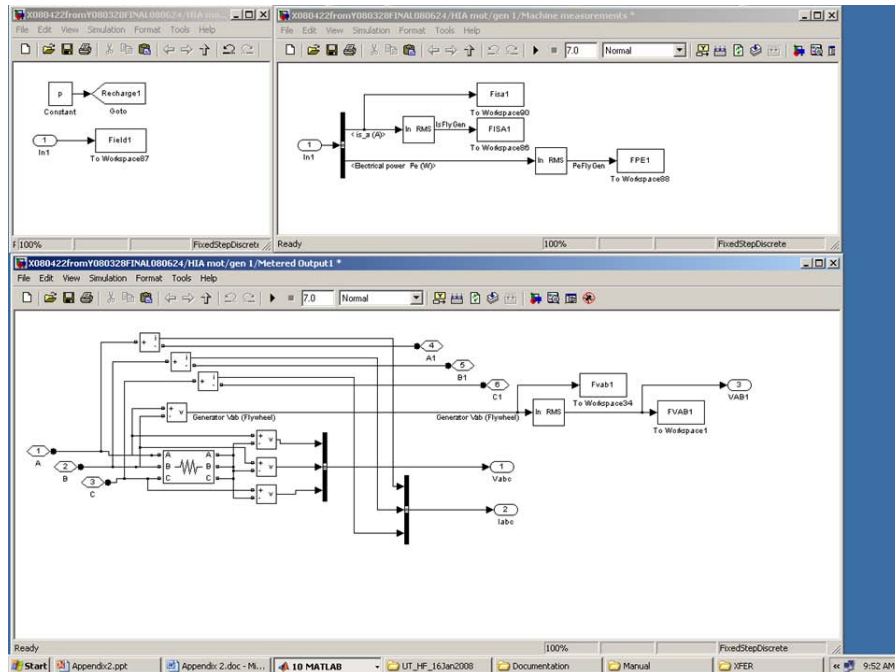


Figure 40. Details of both measurement blocks shown in Figure D33 - the artificial resistive load for the flywheel motor/generator needed for computational stability is visible in the lower block.

Input from and output to other blocks (Figure 33):

V_f, V	Field voltage input to motor/generator field from field controller.
$w, \text{rad/s}$	Flywheel speed, input to motor/generator from flywheel block.
V_{abc}, V	3-phase AC voltage outputs from the flywheel motor/generator to the flywheel block.
I_{abc}, A	3-phase AC current outputs from the flywheel motor/generator to the flywheel block.
$VABk, V$	RMS voltage line-to-line between phases a and b of the motor/generator ($k = 1, 2$ depending on flywheel unit). Output to field and SCR controller block.

Input items in the dialog box (Figure 37):

(in parentheses are the values used in preliminary runs)

KVA, kVA	HIA rated power (1,250)
VLL, V	HIA rated voltage line-to-line (834)
f, Hz	HIA rated frequency (400)
IF, A	HIA rated field current (22.6)

R_s, Ω	HIA stator resistance per phase ($1.346 \cdot 10^{-3}$)
L_l, H	HIA stator leakage inductance per phase ($2.956 \cdot 10^{-5}$)
L_{md}, H	HIA direct axis magnetizing inductance ($2.509 \cdot 10^{-4}$)
L_{mq}, H	HIA quadrature axis magnetizing inductance ($1.676 \cdot 10^{-4}$)
R_f, Ω	HIA field resistance ($1.227 \cdot 10^{-3}$)
L_{fld}, H	HIA field leakage direct axis inductance ($6.643 \cdot 10^{-5}$)
R_{kd}, Ω	HIA equivalent damper direct axis resistance (0.340)
L_{kld}, H	HIA equivalent damper leakage direct axis inductance ($9.372 \cdot 10^{-4}$)
R_{kq}, Ω	HIA equivalent damper quadrature axis resistance (0.025)
L_{klq}, H	HIA equivalent damper leakage quadrature axis inductance ($7.18 \cdot 10^{-5}$)
p	HIA number of poles (4)
$\theta, \text{degrees}$	Initial electrical angle position of HIA rotor (Any value will do: e.g.: 0 was used for HIA machine of flywheel number 1 and 53 for number 2).

A typical output of a flywheel generator at the input terminals of the controlled rectifier is given in Figure 41.

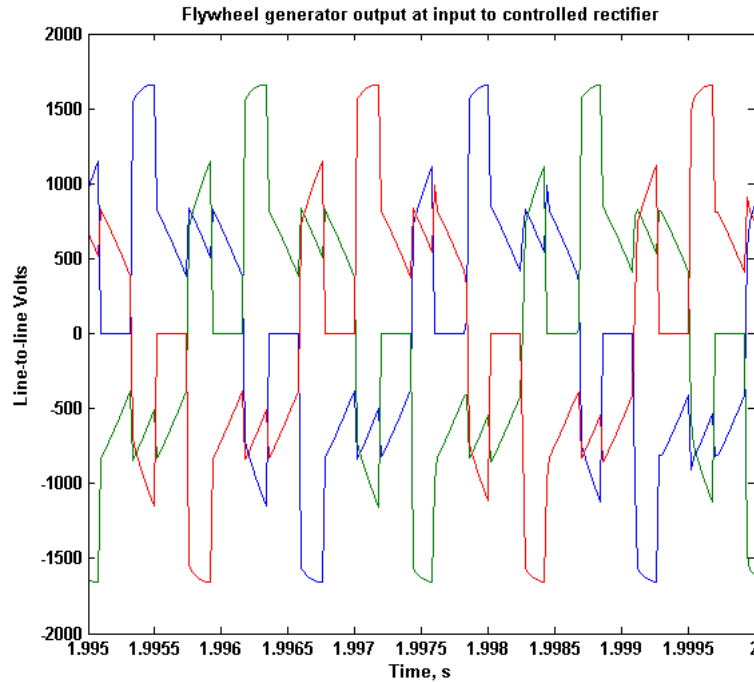


Figure 41. Output of flywheel generator at input to controlled rectifier

Controlled Rectifier

The output of each flywheel motor/generator is rectified by a 3-phase controlled rectifier, is filtered, and the dc output is then connected to the dc bus common to the rest of the system. The active rectifier, implemented by means of SCRs, is shown in Figure 42 and its dialog box, obtained by double-clicking its icon, is shown in Figure 43. The structure of the controlled rectifier block can be obtained by right-clicking its icon and choosing the option “Look under Mask”. This can be seen in Figure 44.

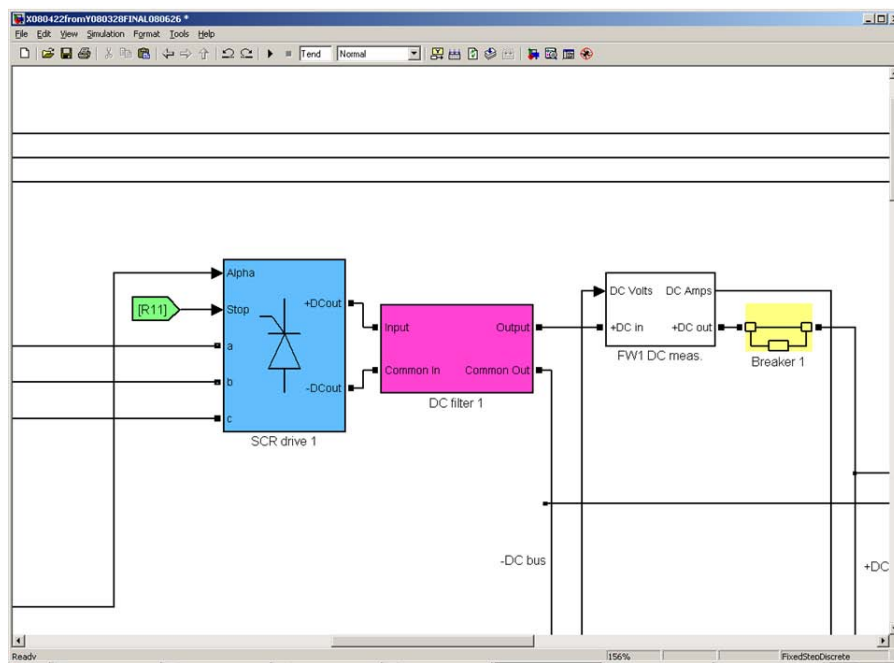


Figure 42. Active rectifier (blue), filter (purple), measurement block (white) and breaker (bright yellow) connecting the 3-phase output of a flywheel motor/generator to the dc bus

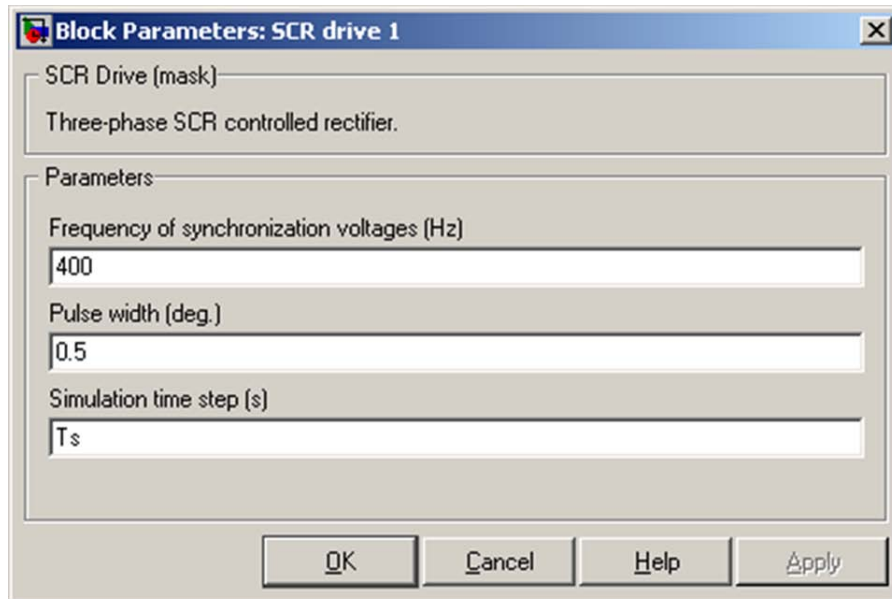


Figure 43. Dialog screen for the SCR controlled rectifier block

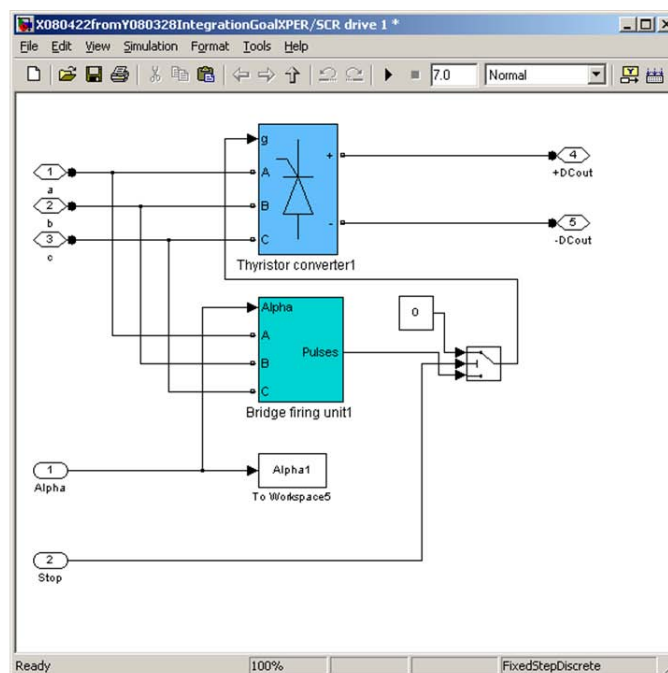


Figure 44. First level diagram under the SCR controlled rectifier block - the SCR bridge proper is the blue block and the firing angle controller is the cyan block

It can be seen that the active rectifier block consists of a thyristor bridge proper and an associated firing controller. Double-clicking the thyristor bridge block yields the dialog box

shown in Figure 45. In general, once determined, the values entered in this input dialog box rarely need to be changed. The thyristor bridge block is a native Simulink block.

Double-clicking the firing control block yields its internal structure shown in Figure 46. All blocks used here are native to Simulink and all variables contained herein are controlled by the upper level dialog screens, thus no additional information is necessary.

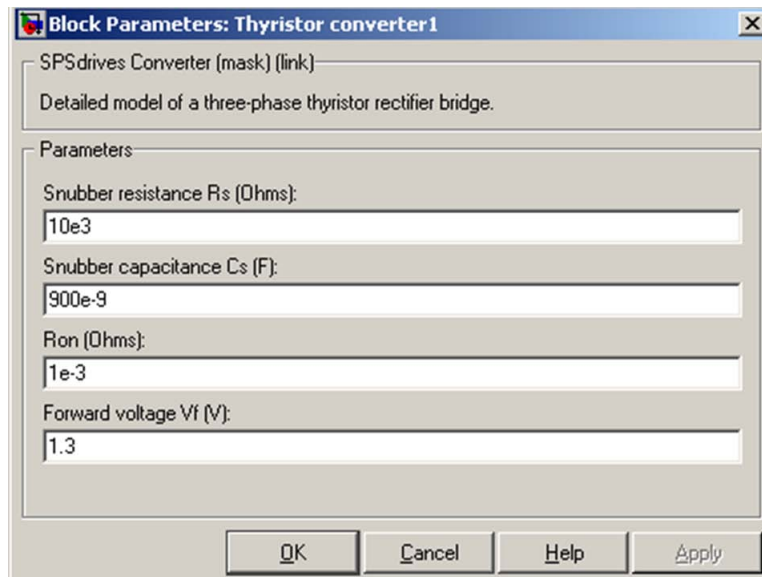


Figure 45. Dialog box for the SCR bridge in Figure 44 - once determined, these values need rarely be changed

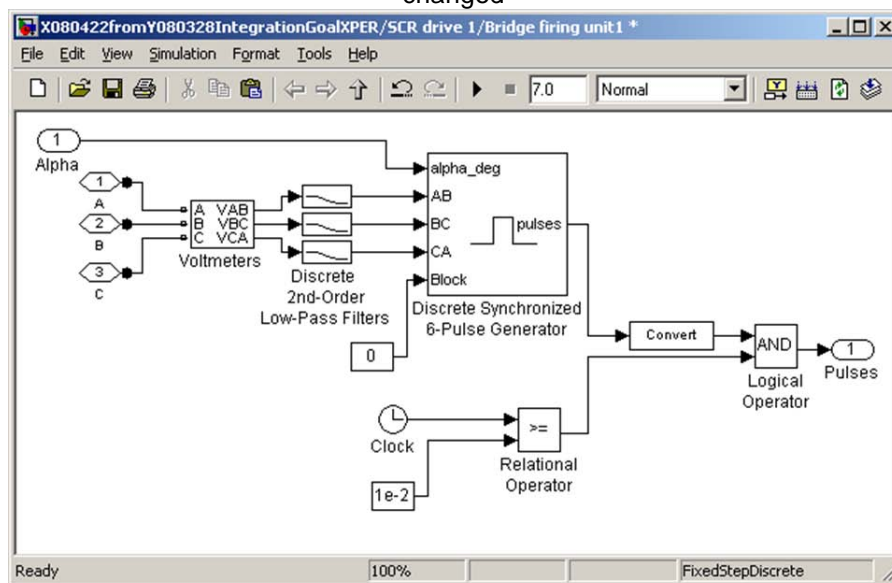


Figure 46. Diagram of the level beneath the firing controller block - all blocks shown here are native Simulink blocks, the pulses here generated are used to fire the SCRs in the rectifying bridge

Input from and output to other blocks (Figure 42):

α , Degrees	Firing angle input to controlled rectifier from field and SCR controller block (see next section).
Stop (R11)	Stop command input from flywheel recharge control block (see later section) to halt firing of controlled rectifier during flywheel re-charging (via a GoTo/From block shown as a flag).
a, b, c	3-phase AC voltage inputs from the flywheel motor/generator to the controlled rectifier block.
+DCout, -DCout	DC output terminals from the controlled rectifier.

Input items in the dialog box (Figure 43):

(in parentheses are the values used in preliminary runs)

F_{sync} , Hz	Frequency of input power (400)
P_w , Degrees	Width of firing pulse (0.5)
T_s , s	Simulation time step (T_s)

DC Filter and Measurements

As described above, the dc rectified power is fed to a filter before being injected into the dc bus. The dialog screen of the filter can be obtained by double-clicking its icon (Figure 47), while its structure can be shown, as usual, by right clicking and choosing “Look under Mask”(Figure 48 top). The detailed circuit of the T-type filter used (one tier lower) is underneath the purple icon of the filter in level one and is shown in Figure 48 bottom.

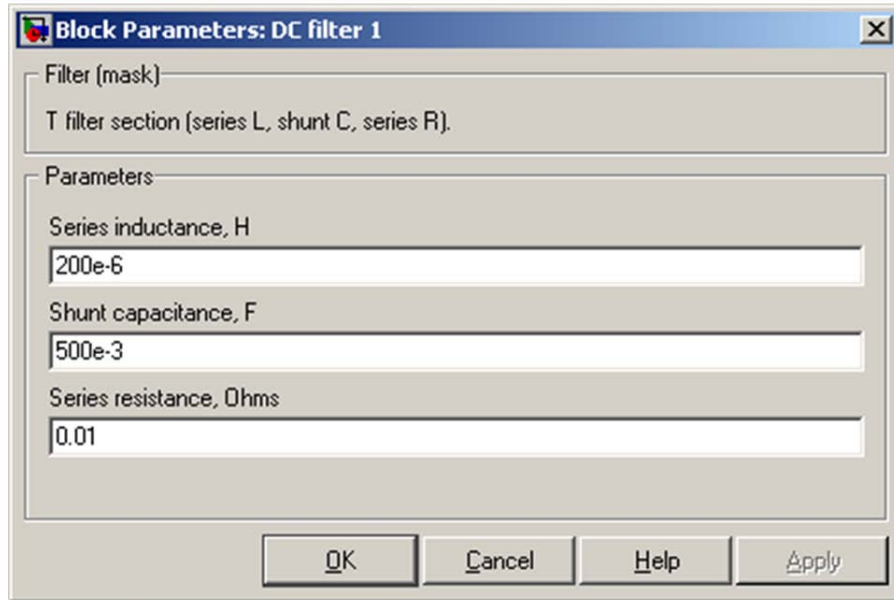


Figure 47. Dialog input screen for the DC filter

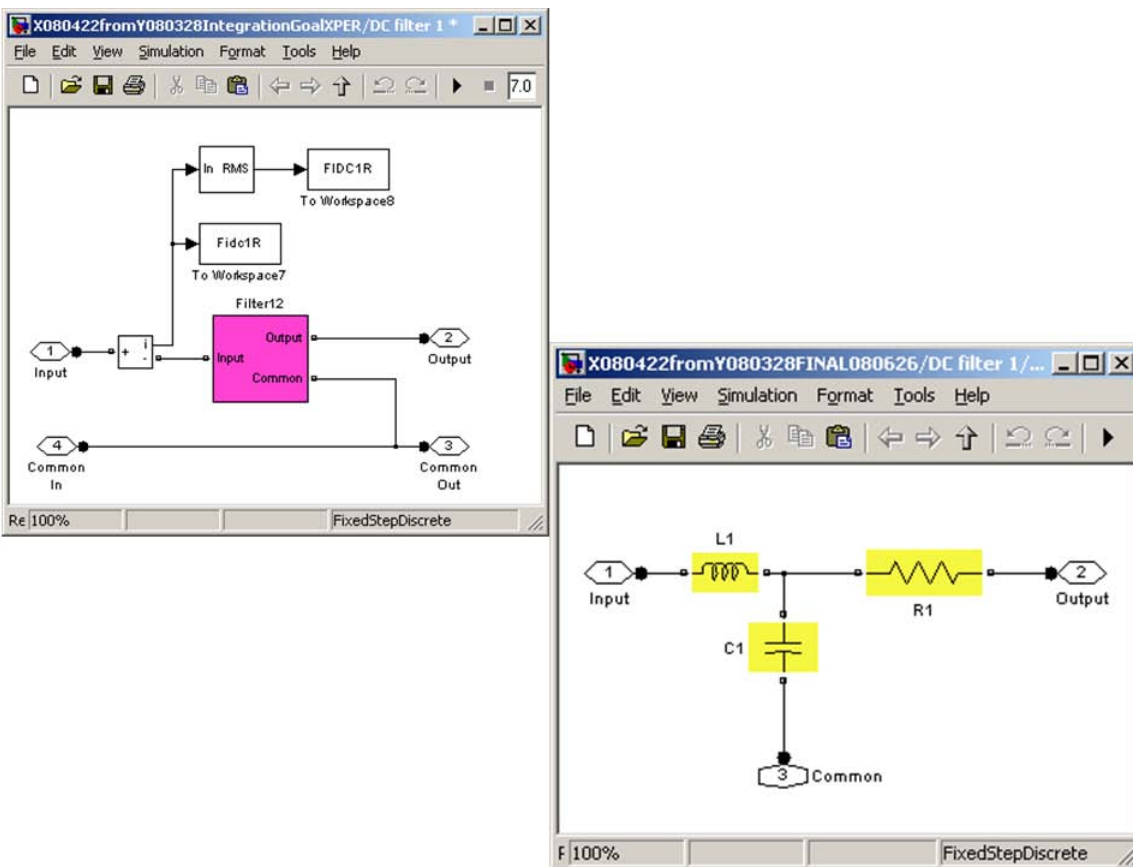


Figure 48. First level structure (top) and second level structure (bottom) for the dc filter

Input from and output to other blocks (Figure 40):

Input (+), Common In (-) DC input terminals from the controlled rectifier.

Output (+), Common Out (-) DC output terminals to the dc bus.

Input items in the dialog box (Figure 45):

(in parentheses are the values used in preliminary runs)

L1, H Filter series inductance ($200 \cdot 10^{-6}$)

C1, F Filter shunt capacitance ($500 \cdot 10^{-3}$)

R1, Ω Filter series resistance (0.01)

A typical output of the controlled rectifier and filter is given in Figure 49.

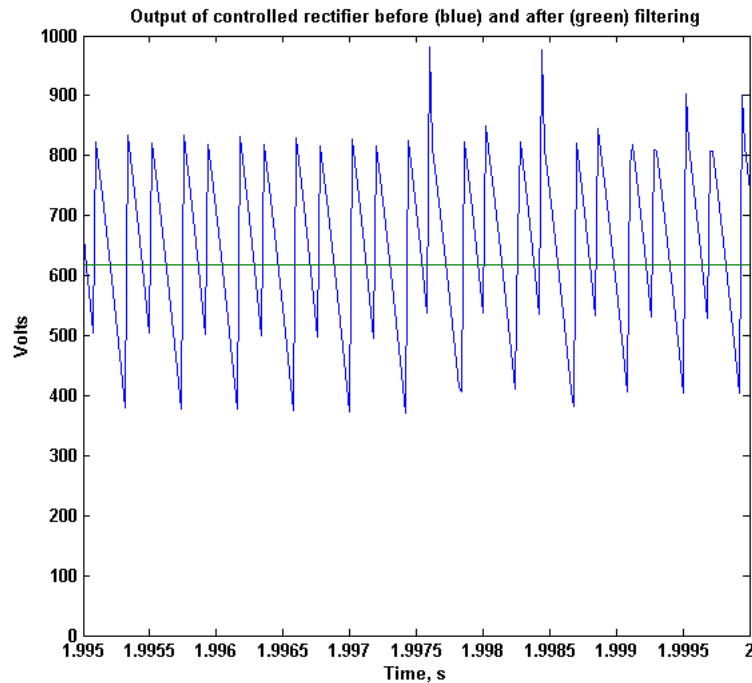


Figure 49. Rectified voltage output of controlled rectifier (blue) and of filter (green)

Field and SCR controller

Figure 50 shows the blocks that control the operation of the flywheel energy storage section in the simulation circuit. In this section we will cover the field and SCR controller block and the others will be covered in subsequent sections.

Figure 51 shows the input dialog box that can be obtained by double-clicking on the icon of the field and SCR controller block. To view its internal structure, right-click on the block and select “Look under Mask”: the first tier of the structure appears as shown in Figure 52.

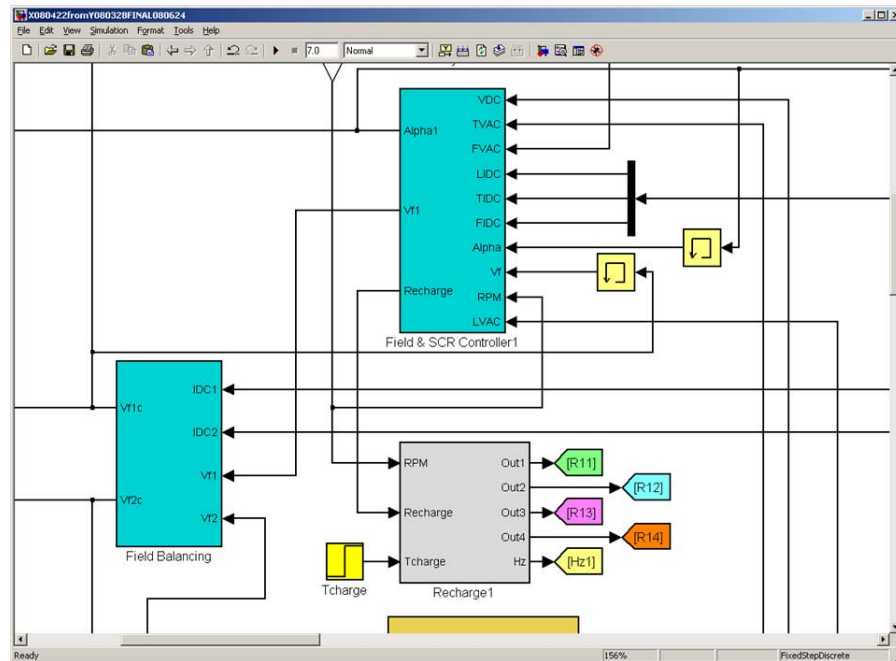


Figure 50. The flywheel control blocks: the field and SCR controller, the field balancing controller between the two flywheels, and the flywheel re-charge controller

Figure 51. Input dialog box for the field and SCR controller block

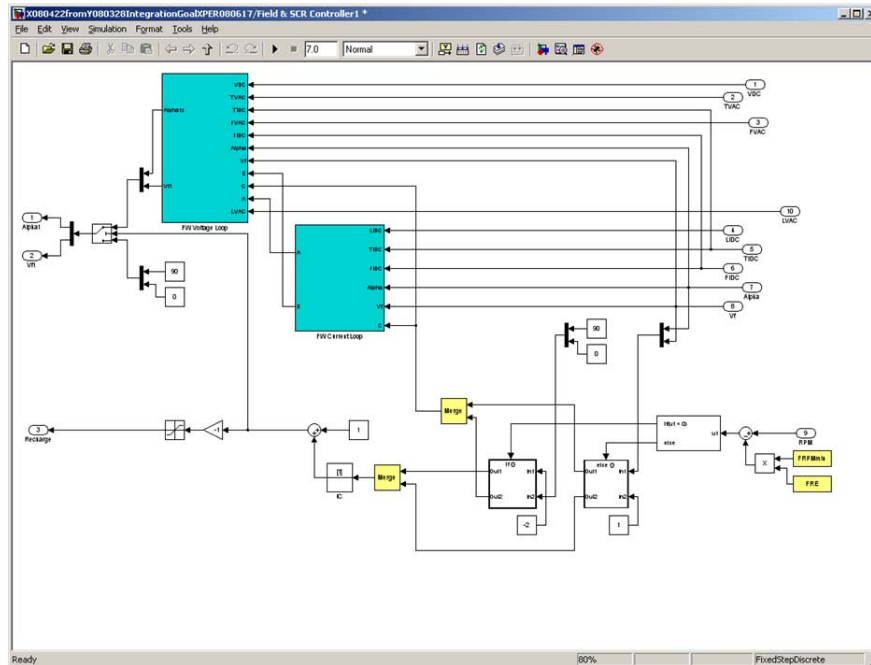


Figure 52. First level structure of the field and SCR controller block

The overall scheme of the flywheel generator/active rectifier controller can be described as the combination of a current loop within a voltage loop. First, the controller checks that the ac bus voltage, the dc bus voltage, the dc bus voltage rate of change in time, the turbine generator voltage, and the flywheel generator voltage are within pre-established bounds (Voltage loop). If they are, the controller proceeds to check that the dc load current, the turbine generator dc current, and the flywheel generators dc current are within pre-established bounds (Current loop). If any of the bounds are exceeded, corrective action is taken based on both Voltage and Current status (Control action).

Figure 53 and Figure 54 give the Simulink structures below the cyan blocks shown in Figure 52 that implement the aforementioned control scheme. An additional lower level is also accessible for each of the cyan blocks in Figure 53 and Figure 54. For sake of clarity, the complete control strategy of Figure 52, Figure 53, and Figure 54 has been also summarized in an equivalent flow chart that is extensively labeled so as to be self contained and self explanatory (Figure 55 through 58).

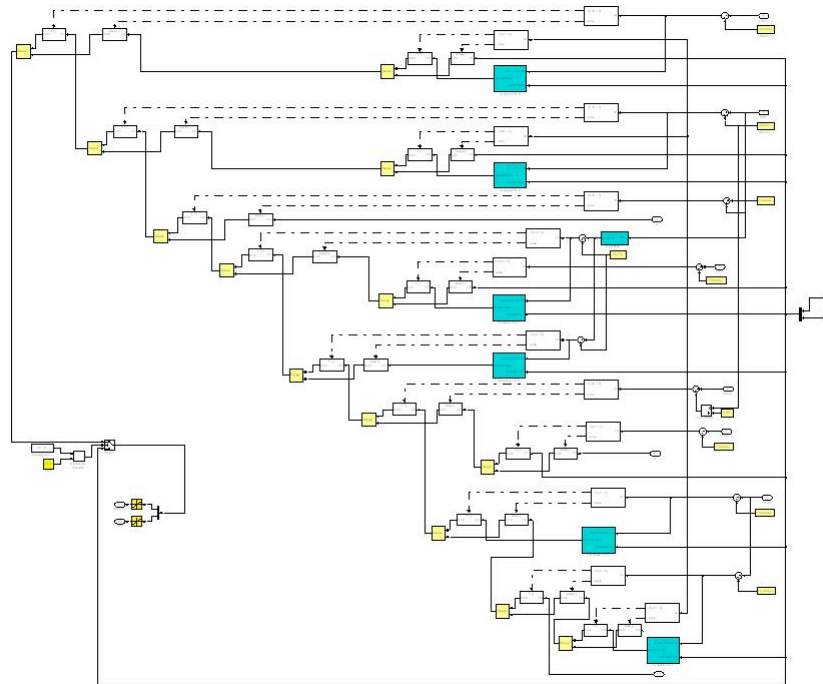


Figure 53. Second level of field and SRC controller block: voltage loop

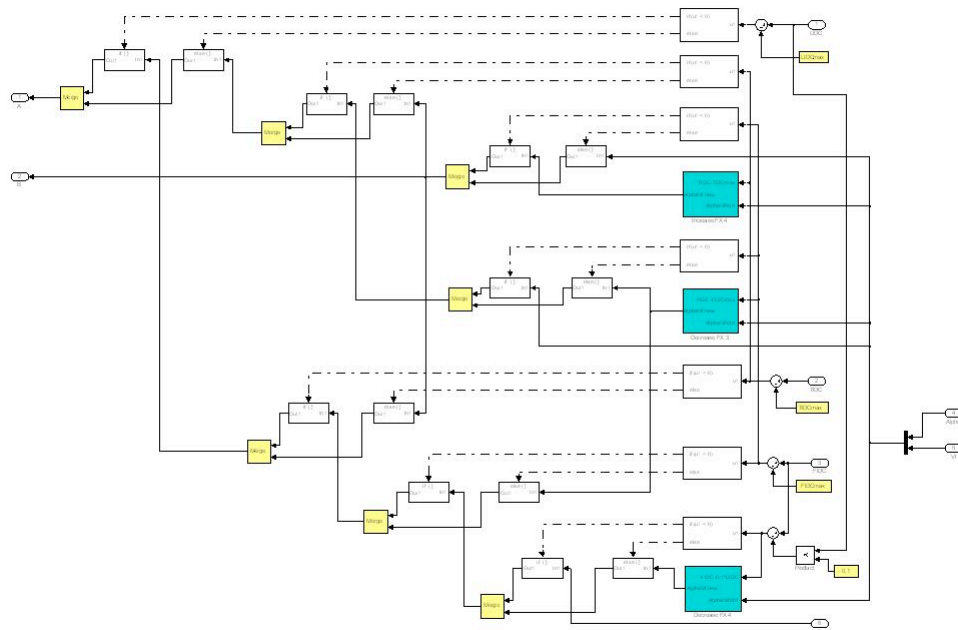


Figure 54. Second level of field and SRC controller block: current loop

VOLTAGE
LOOP
Part 1

LVAC = AC bus load Volts rms
 LVACmin = minimum value allowed for LVAC
 VDC = DC bus Volts
 $dVDC/dt$ = rate of change of VDC
 VDCmin = minimum value allowed for VDC
 VDCmax = maximum value allowed for VDC
 Δ = maximum allowed value of $dVDC/dt$
 FX = Flywheel generator output (controlled by field voltage and/or rectifier angle)
 TVAC = Turbine generator Volts rms
 TVACmin = minimum value allowed for TVAC
 FVAC = Flywheel generator Volts rms
 FVACmin = minimum value allowed for FVAC
 FVACmax = maximum value allowed for FVAC

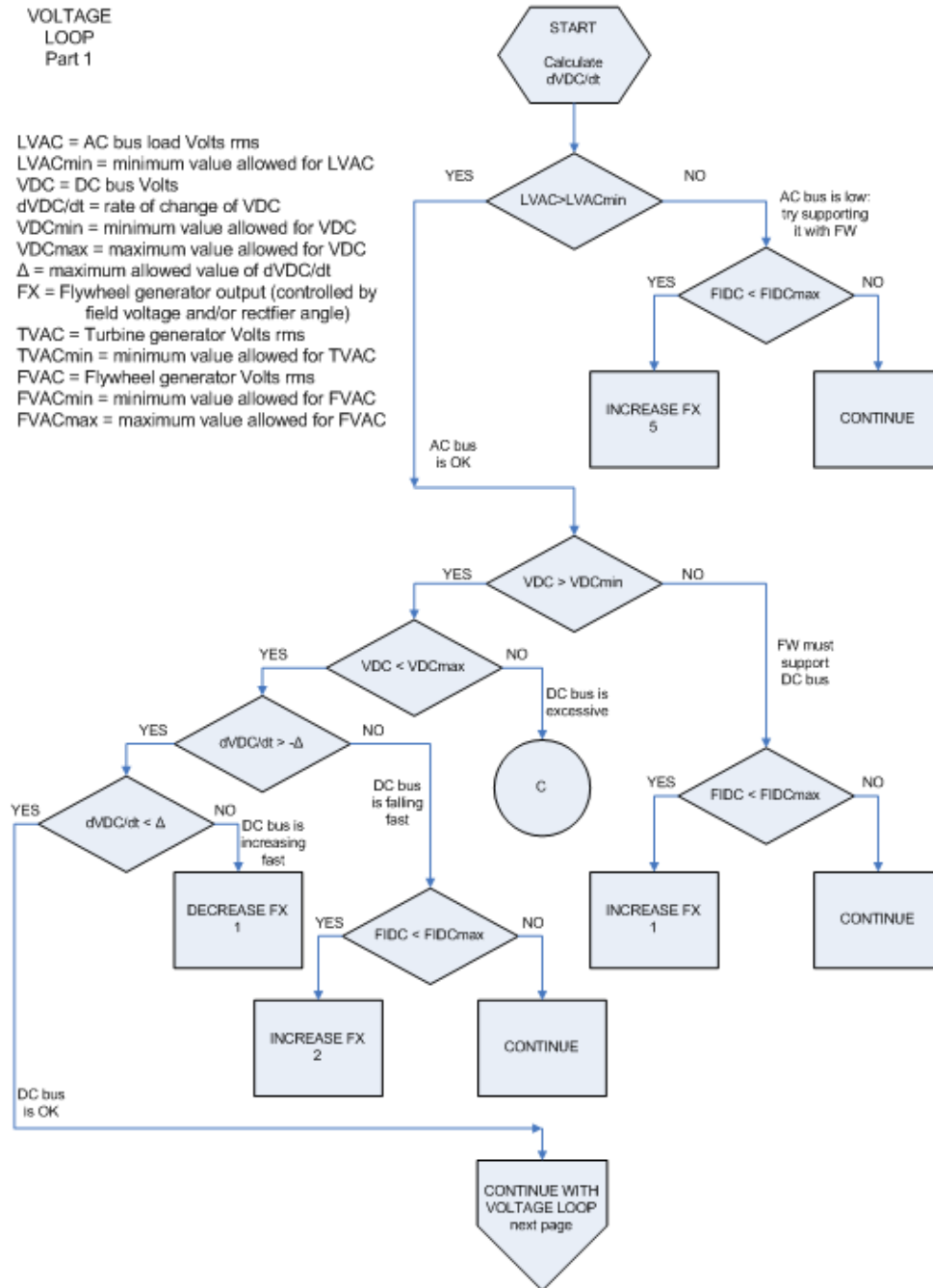


Figure 55. Voltage loop flow chart, part 1 of 2

VOLTAGE
LOOP
Part 2

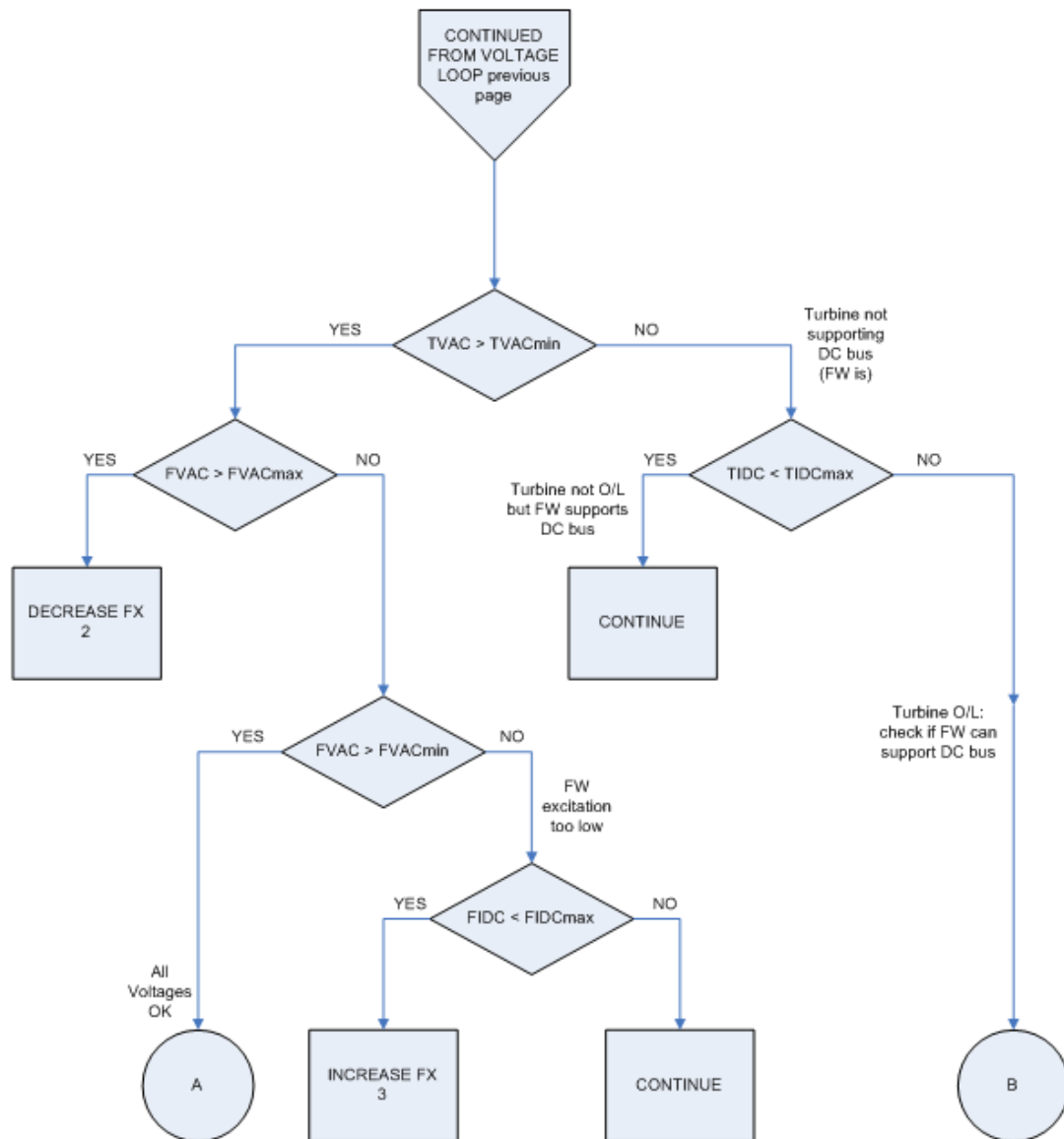


Figure 56. Voltage loop flow chart, part 2 of 2

CURRENT
LOOP

LIDC = Load DC Amperes
 LIDCmax = maximum value allowed for Load
 DC Amperes
 TIDC = Turbine generator DC Amperes
 TIDCmax = maximum value allowed for
 Turbine generator DC Amperes
 FIDC = Flywheel generator DC Amperes
 FIDCmax = maximum value allowed for
 Flywheel generator DC Amperes

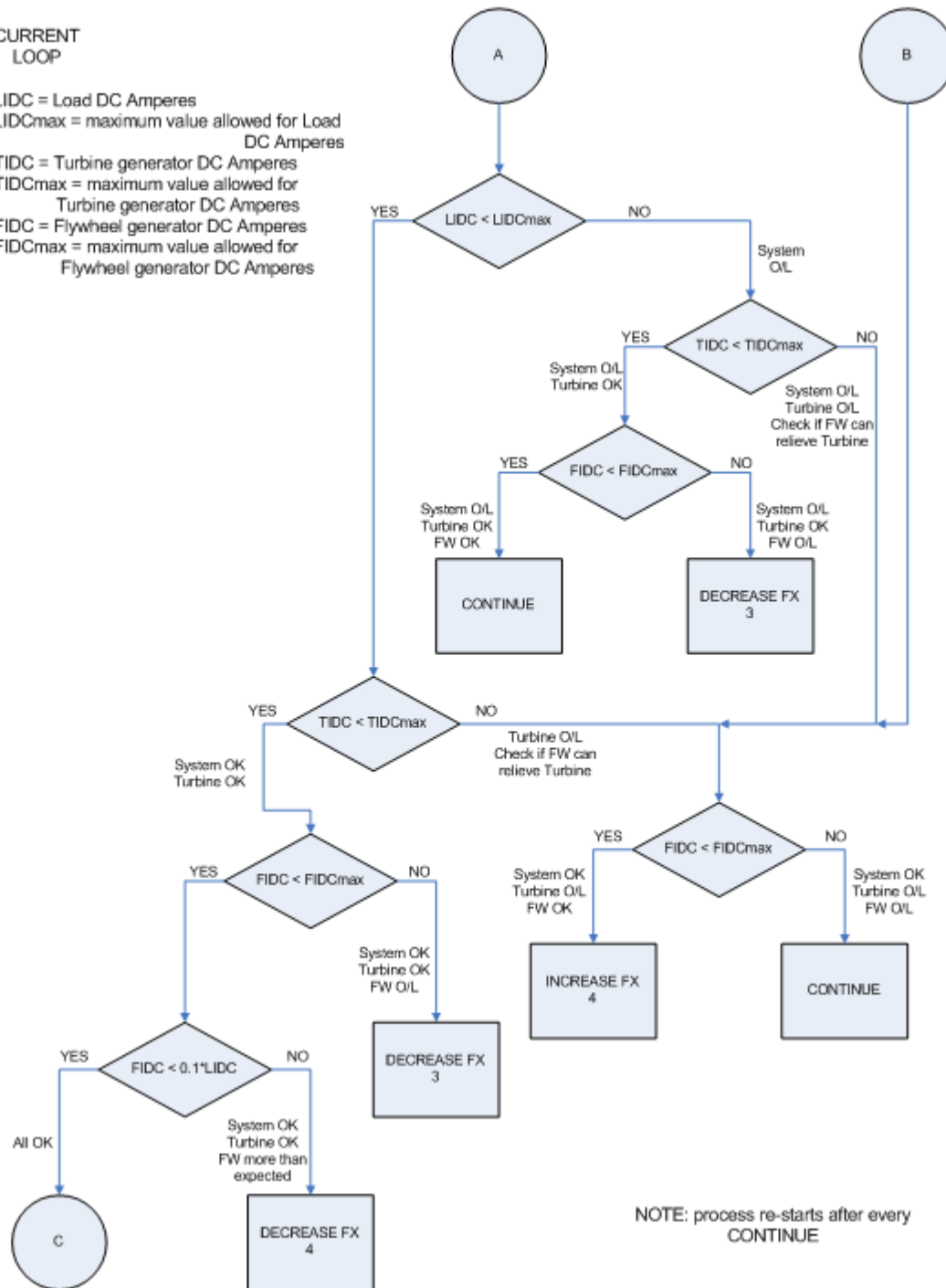


Figure 57. Current loop flow chart

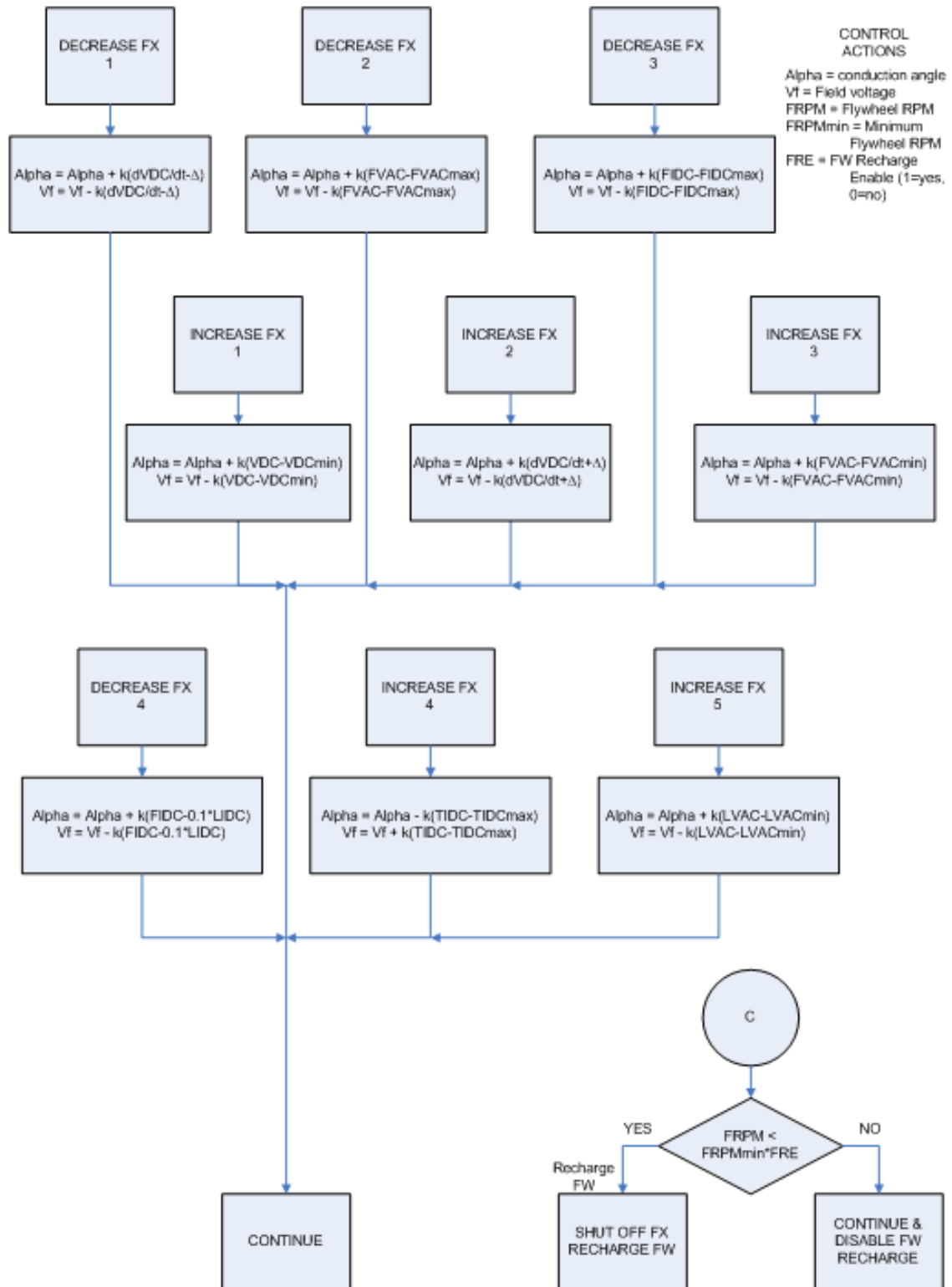


Figure 58. Control action flow chart

Input from and output to other blocks (Figure 50):

<i>VDC, V</i>	DC bus voltage input from dc bus measurement block
<i>TVAC, V</i>	Mean RMS turbine generator voltage input from turbine generator block
<i>FVAC, V</i>	Mean RMS flywheel generator voltage input from HIA machine block
<i>LIDC, A</i>	Load side dc bus current input from dc bus measurement block
<i>TIDC, A</i>	DC bus current contributed by turbine section; input from dc bus measurement block.
<i>FIDC, A</i>	DC bus current contributed by flywheel sections; input from dc bus measurement block.
<i>α, Degrees</i>	Firing angle for SCR rectifier input from previous computational cycle
<i>V_f, V</i>	Field voltage of HIA machine input from previous computational cycle of field balancing circuit
<i>FRPM, RPM</i>	Flywheel RPM input from flywheel block
<i>LVAC, V</i>	AC bus RMS voltage input from ac bus measurement block
<i>α', Degrees</i>	Revised firing angle output to SCR rectifier block
<i>V_f', V</i>	Revised field voltage output to field balancing circuit
<i>Recharge</i>	Command to recharge flywheel output to recharge control block

Input items in the dialog box (Figure 51):

(in parentheses are the values used in preliminary runs)

<i>FVAC_{min}, V</i>	Minimum allowable ac line-to-line flywheel generator voltage (480)
<i>FVAC_{max}, V</i>	Maximum allowable ac line-to-line flywheel generator voltage (500)
<i>FIDC_{max}, A</i>	Maximum allowable dc load current from flywheel sections (2,899)
<i>FRPM_{min}, RPM</i>	Minimum allowable flywheel RPM without re-charging (11,800)
<i>FRE</i>	Flywheel re-charge command: enable = 1, disable = 0 (either)
<i>Tinit, s</i>	Initialization time before field and SCR controller goes into effect (0.1)

Field Balancing Controller

As in all cases where multiple power supplies are in parallel, also in the case of two flywheel energy storages it is possible to have unequal distribution of the load between them. To minimize the unbalance a field balancing controller block was used to adjust the field voltages to the two flywheel generators in order to keep an even load sharing.

Figure 50 shows the field balancing block and Figure 59 shows the input dialog box that can be obtained by double-clicking on it. To view the internal structure of the field balancing controller, right-click on the block and select “Look under Mask”: the structure appears as shown in Figure 60. A flow chart is also given in Figure 61.

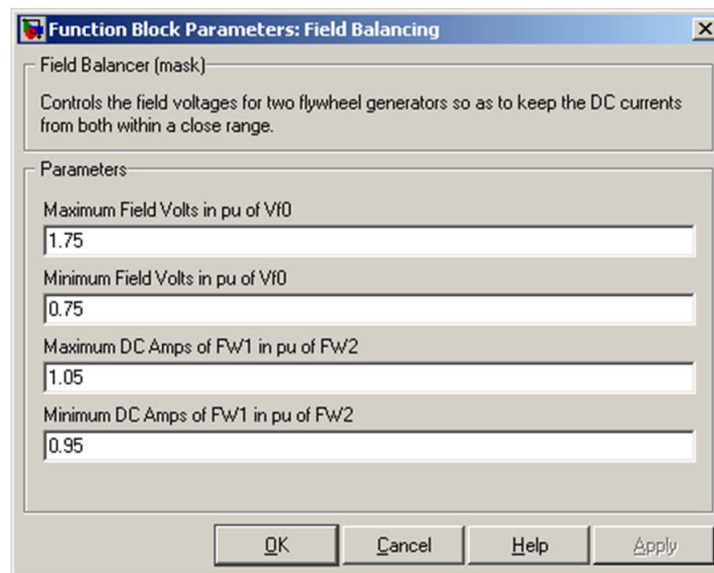


Figure 59. Input dialog box of field balancing controller

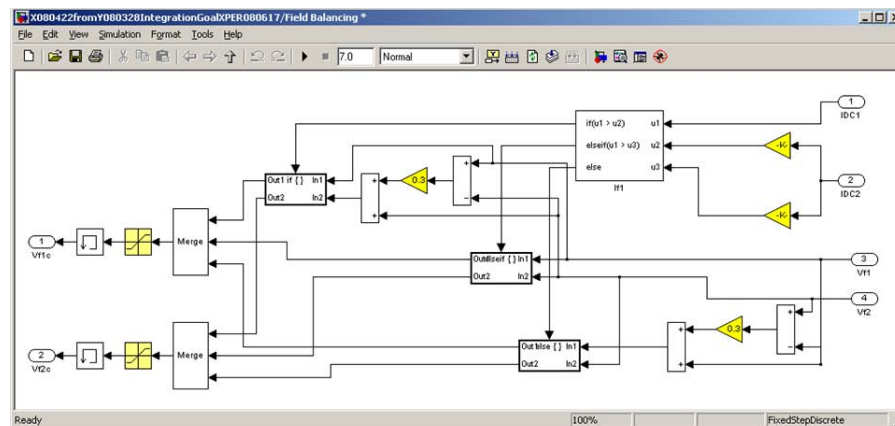


Figure 60. Structure of field balancing controller

FIELD BALANCING

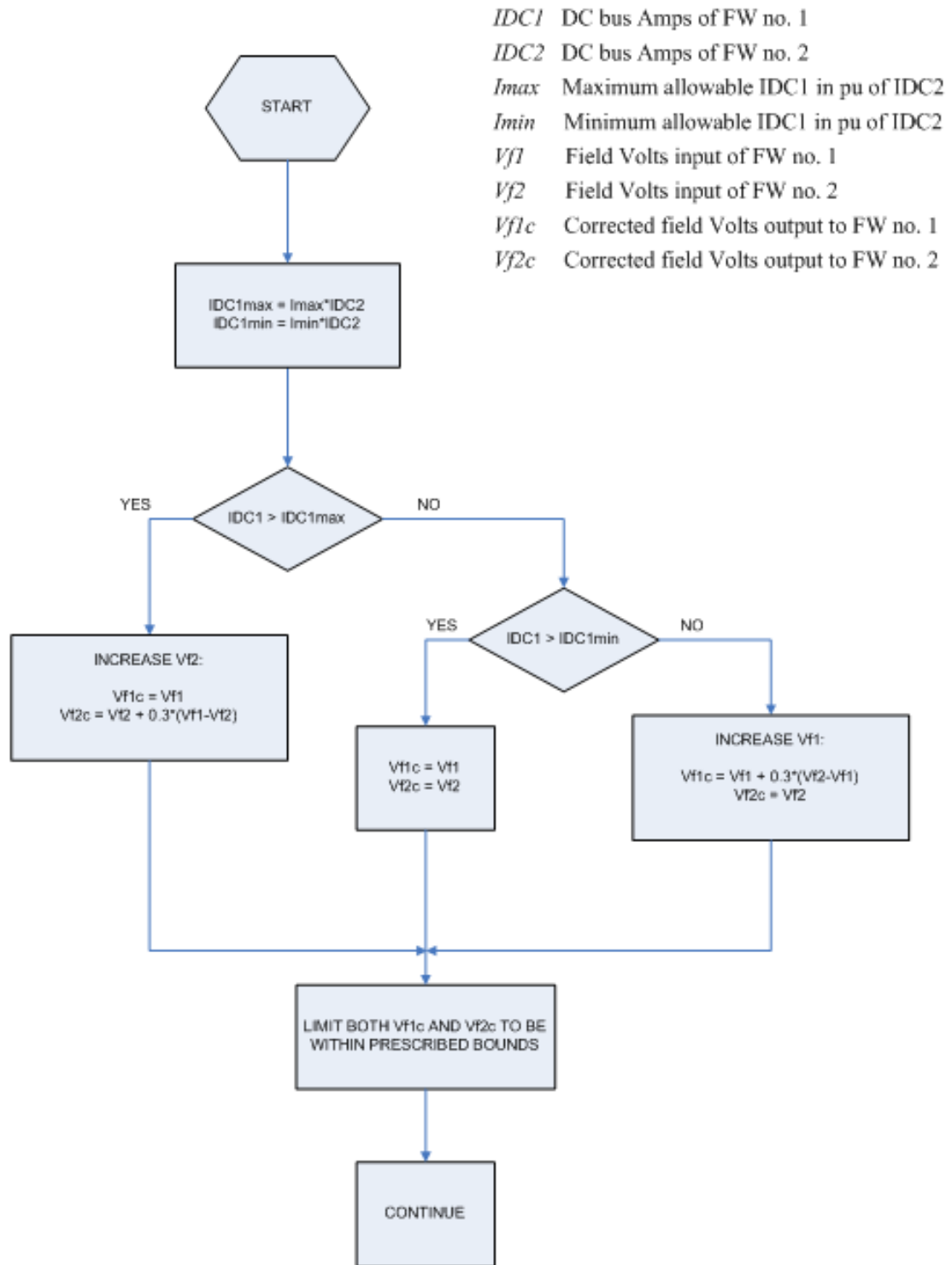


Figure 61. Flow chart of field balancing controller

Input from and output to other blocks (Figure 50):

$IDC1, A$	DC bus current of flywheel storage no. 1, input from dc bus measurement block
$IDC2, A$	DC bus current of flywheel storage no. 2, input from dc bus measurement block
$Vf1, V$	Field voltage input from field and SCR controller block no. 1
$Vf2, V$	Field voltage input from field and SCR controller block no. 2
$Vf1c, V$	Corrected field voltage output to HIA machine no. 1
$Vf2c, V$	Corrected field voltage output to HIA machine no. 2

Input items in the dialog box (Figure 59):

(in parentheses are the values used in preliminary runs)

$Vfmax, pu$	Maximum allowable field voltage in per unit of $Vf0$ (1.75)
$Vfmin, pu$	Minimum allowable field voltage in per unit of $Vf0$ (0.75)
$Imax, pu$	Maximum allowable dc current of flywheel no. 1 in per unit of the dc current of flywheel no. 2 (1.05)
$Imin, pu$	Maximum allowable dc current of flywheel no. 1 in per unit of the dc current of flywheel no. 2 (0.95)

Flywheel Recharge Controller

The flywheel recharge controller is shown in Figure 50. Its function is to generate a proper sequence of signals for the recharge of the flywheel, either if requested by an external operator signal (via the input $Tcharge$ in file RunXXX.m) or if triggered automatically when the flywheel speed falls below the minimum value specified in the field and SCR controller dialog box (Figure 51). In either case, in order for the flywheel recharging to take place, the flywheel re-charge variable must be enabled in the same field and SCR controller dialog box (Figure 51).

The flywheel recharge controller block does not have an input dialog box and its structure is shown in Figure 62. The two possible signals to recharge the flywheels, namely the internal one “Recharge” and the external one “Tcharge”, are OR-ed and their resultant is split into four signals with various delays to allow the proper sequence of steps at the various components

affected. Additionally, the recharge controller generates the initial frequency signal for the recharging variable frequency drives.

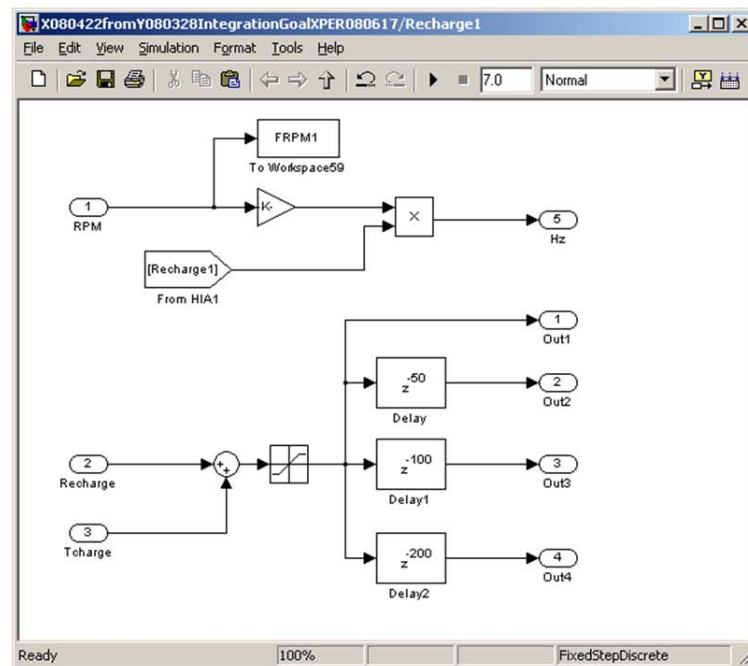


Figure 62. Structure of flywheel recharge controller

Input from and output to other blocks (Figure 62):

<i>RPM</i>	Input RPM from flywheel
<i>Recharge</i>	Input signal to re-charge flywheel from field and SCR controller
<i>Tcharge</i>	Operator's signal to recharge at time $t = Tcharge$ as specified in input file RunXXX.m

The following signals are all exchanged via GoTo/From blocks (shown as flags in the Simulink model)

<i>Rechargek</i>	Number of poles input from the corresponding HIA machine ($k = 1,2$)
<i>R11</i>	Zero delay signal output to stop the trigger pulses to the controlled rectifier at the output of the flywheel generator
<i>R12</i>	50 cycles delay signal output to close the breaker powering the recharging variable frequency drive (VFD) from the dc bus (see next section)
<i>R13</i>	100 cycles delay signal output to start the recharging VFD (see next section)

<i>R14</i>	200 cycles delay signal output to close the output breaker of the VFD onto the flywheel motor (see next section)
<i>H_z</i>	Frequency at which the VFD has to start re-charging the HIA motor corresponding to the HIA RPM. Output to VFD block.

Flywheel Recharging Variable Frequency Drives (VFD)

One VFD powered by the common dc bus is provided for each flywheel to re-accelerate it to top speed. The VFD is structured very similarly to the dc-ac converter covered previously in Section 7 and to a general VFD used to accelerate motor loads. Here only the special characteristics of these VFDs used to recharge the flywheels will be covered and the reader is referred to Section 7 for the common details.

Figure 63 shows the icon of the recharging VFD in the simulation circuit and Figure 64 shows the input dialog box that can be obtained by double-clicking on the icon. The VFD block includes also within it an output filter section: this is indicated by the purple rectangle contained within the block icon. To view the internal structure of the VFD block, right-click on the icon and select “Look under Mask”: the first tier of the structure appears as shown in Figure 65.

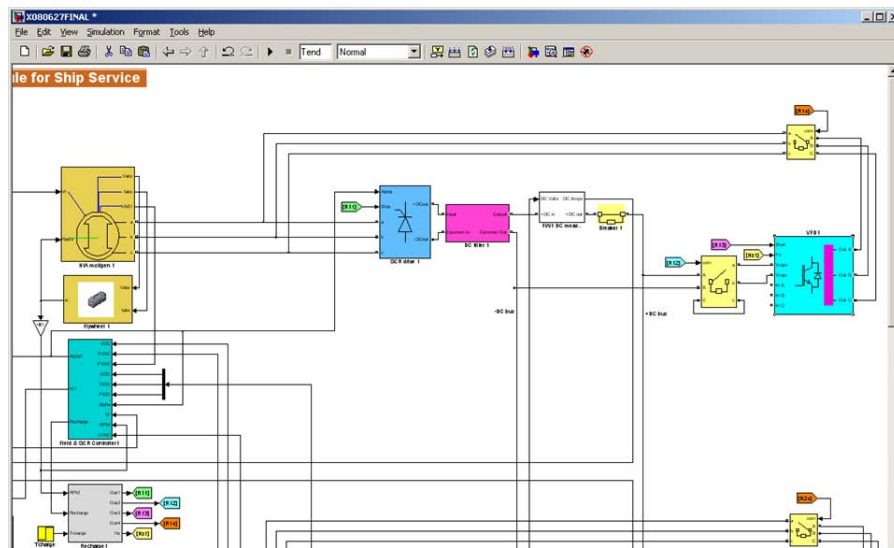


Figure 63. VFD circuit used for recharging a flywheel. The VFD is the bright light blue block. The purple rectangle within it indicates that the block has a filter incorporated within it. The VFD interfaces to the dc bus and to the HIA machine via circuit breakers (bright yellow blocks).

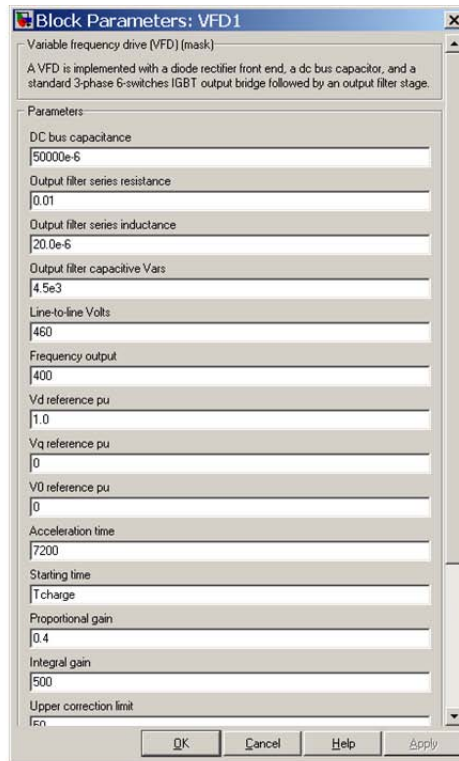


Figure 64. recharging VFD dialog box

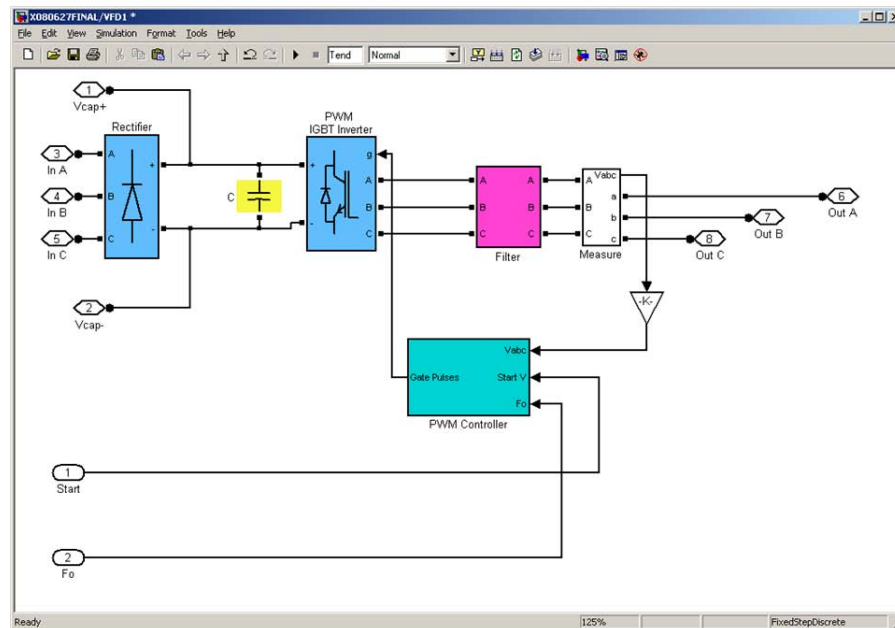
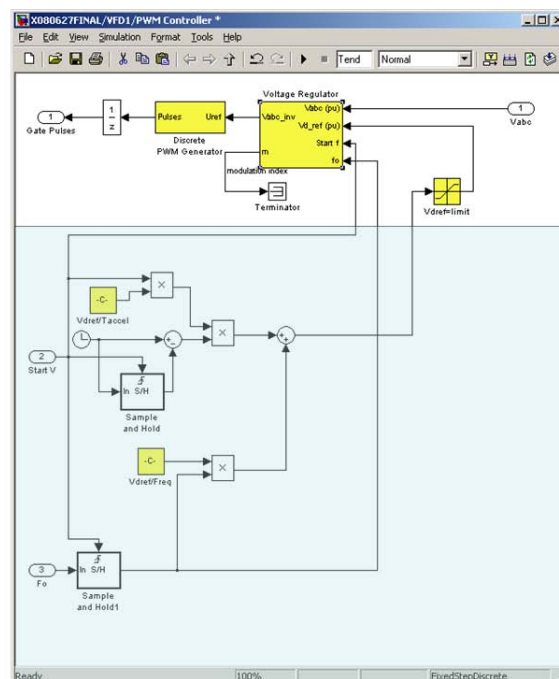


Figure 65. First level structure of VFD block

It can be seen that the structure is essentially the same as that used for the dc-ac converter (Figure 24), where instead of a quad configuration we have now a single converter. In addition, the converter now has the option of being powered by either a dc source or by a three-phase ac source that is internally rectified (blue rectifier block on left). This requires the presence of a smoothing dc bus capacitor (highlighted in bright yellow). The three-phase inputs for the re-charging VFD are left open since they are powered from the dc bus.



The rest of the structure is the same as that of the dc-ac controller save for another addition within the PLL block (see bottom left of Figure 29) similar to the one shown in Figure 66, inserted to allow a smooth acceleration from a given starting frequency up to the maximum frequency. This difference in the PLL block is shown again highlighted in Figure 67.

Various Loads

Several loads can be connected to the ac bus provided they do not exceed the capacity of the system. The loads shown in the overall system diagram of Figure 68 have been realized, whenever possible, with native Simulink blocks and are listed below in Figure 69 and Figure 70. Each load is connected to the ac bus via a breaker. Their operation should be rather transparent based also on similar items described previously in this documentation.

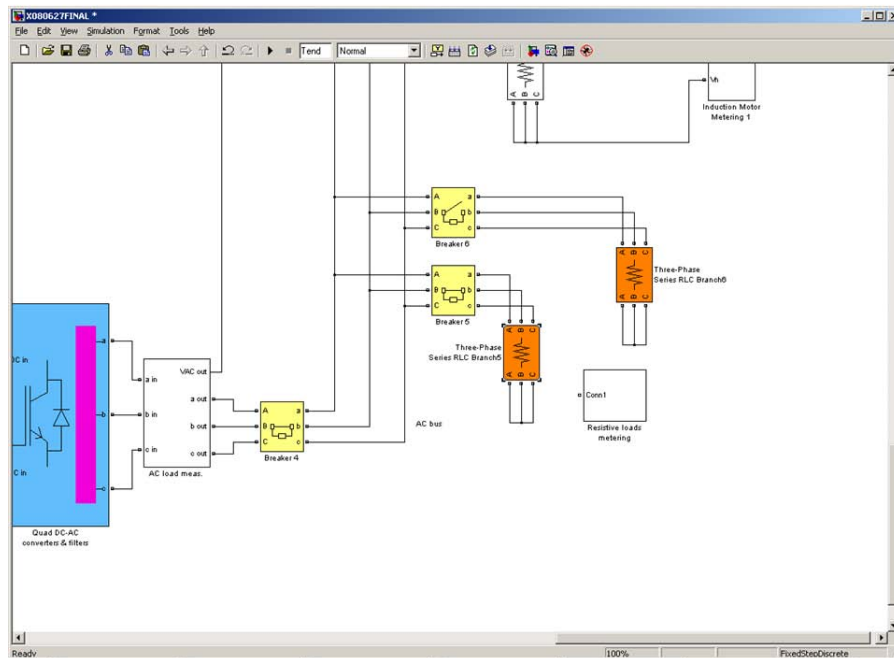


Figure 68. Resistive loads (e.g. lighting). 0.135 Ohms were used in preliminary runs, equal to 1.5 MW each

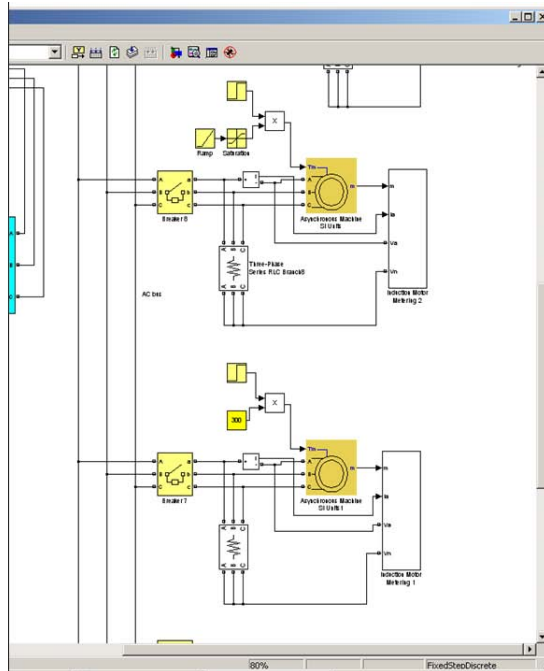


Figure 69. Bottom: 100 HP induction motor started across the line with load torque, applied at predetermined time (e.g. positive displacement pump), Top:200 HP induction motor started across the line with load torque applied as a ramp (soft start)

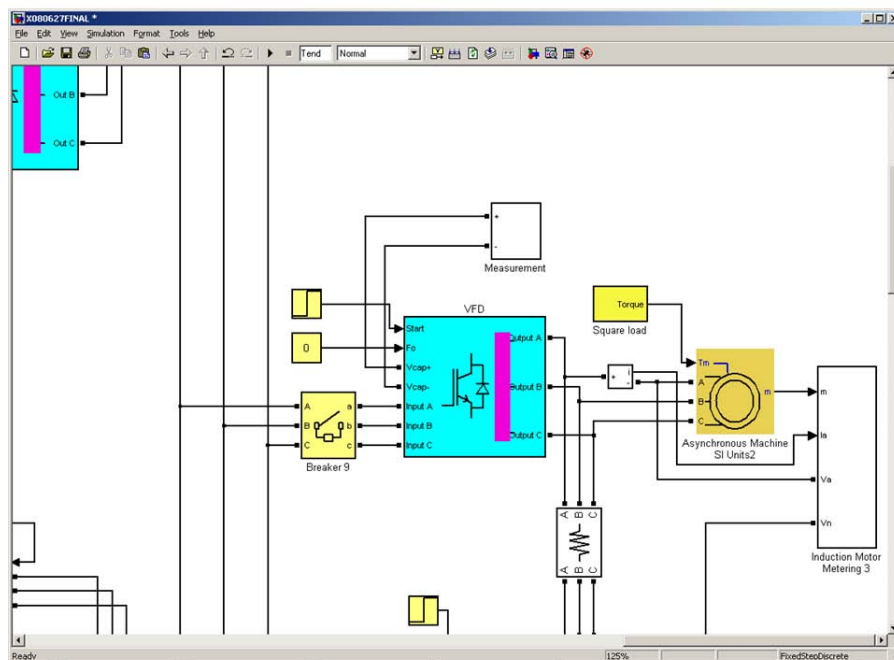


Figure 70. 200 HP induction motor with square law torque load (e.g. centrifugal pump) started via a variable frequency drive much like the one described in the previous section for recharging the flywheel